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# The Production and Modification of Ionospheric Irregularities by Powerful HF Radio Transmissions

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Several types of active experiments have been performed with the high power HF heater near Arecibo, Puerto Rico. The temporal behavior of suprathermal electron fluxes was studied by observing the 430 MHz radar backscatter from ionospheric Langmuir waves that were Cerenkov-emitted by the suprathermal electrons during pulsed operation of the HF heater. Coded radar pulse techniques were used to study the height dependence of radar backscatter from Langmuir turbulence for both CW and pulsed HF heating. Observations with the 430 MHz radar of the power backscattered from HF induced Langmuir turbulence with a temporal resolution of 1 ms sometimes showed almost periodic short bursts of power at time intervals of 20 - 50 ms. The observational limitations on the role of strong Langmuir caviton turbulence have been pointed out and the important role of field-aligned depletions of the plasma density have been stressed in accounting for the observed height dependence of the 430 MHz radar backscatter and for nature of the observed 46.8 MHz radar backscatter. RHF

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## PREFACE

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## Table of Contents

## SUMMARY

A large number of studies of the diverse phenomena observed during the operation of the high power HF heater near Arecibo, Puerto Rico have been performed by a variety of techniques.

The temporal behavior of 430 MHz radar backscatter by ionospheric Langmuir waves Cerenkov-emitted by suprathermal electrons was observed while the high power HF heater was operated in a pulsed mode. At night, in the absence of photoelectrons, the backscattered power by those Langmuir waves with frequencies about 1 MHz above the heater frequency reaches a maximum about 0.3 seconds after heater turn-on and then decreases to a lower constant level. In daytime the photoelectron flux, diagnosed by the same type of radar backscatter, shows a similar overshoot; this has been attributed to a modification in the velocity distribution function of photoelectrons (Attachment 1).

Studies of the fast temporal variations in the power of the 430 MHz radar backscatter from HF induced Langmuir turbulence (of the so-called enhanced plama line) revealed the occasional presence of almost periodic pulse sequences. Enhanced plasma line spectra from different heights 1.2 km apart were observed by the method of coded long pulses. These observations, combined with earlier observations by others, showed that all of the different observed spectral features originate at heights well above the so-called matching height where Langmuir waves simultaneously satisfy the dispersion relation in the ambient ionosphere and the Bragg condition for backscatter. Difficulties of inter-

preving these and other observations of the enhanced plasma line in terms of strong Langmuir caviton turbulence have been pointed out. An alternative interpretation in terms of field-aligned depletions (ducts) in the plasma density, with transverse dimensions of the order of 10m, has been advocated (Attachment 2).

Further observations with coded long 430 MHz radar pulses with improved height resolutions of 300m or 600m showed the simultaneous presence of below threshold enhanced plasma line spectra at the matching height and above threshold spectra at heights greater than the matching height by 600 m and 1200 m for low heater powers. Under stable ionospheric conditions when only the below threshold spectrum at the matching height (which changed by less than 600 metres during 10 minutes) was observed for a low heater power, a tenfold temporary increase in heater power for a duration of 20 s resulted in subsequent strong above threshold spectra 600m and 1200m above the matching height persisting for almost two minutes; after that again only below threshold spectra at the matching height were observed. Field aligned depletions in the plasma density, formed during the 20 second period of transmission with increased power, explain these observations. Independent observational evidence of the presence of irregularities is provided by simultaneous observations of 46.8 MHz and 430 MHz radar backscatter from HF-induced ionospheric Langmuir turbulence (Attachment 3).

Invited reviews were presented on physical processes of ionospheric heating experiments (Attachment 4) and on ionospheric irregularities resulting from powerful HF radio transmissions

(Attachment 5).

Simultaneous observations were made of the enhanced plasma line and of the reflected HF heater wave at Arecibo. In these observations a specially designed pulsing scheme of the heater was used that made the separation of the contributions to the attenuation of the heater wave by thermal and ponderomotive type parametric instabilities possible. For a heater frequency of 3.175 MHz both type of contributions are present but for a heater frequency of 5.1 MHz neither of those contributions was detectable. The simultaneously observed strong overshoot in the power of the enhanced plasma line for a heater frequency of 5.1 MHz can not therefore be explained by an attenuation of heater wave (Attachment 6).

Observations of stimulated electromagnetic emissions (SEE) were also made at Arecibo. They revealed unique,short-lived HF sideband emissions that were less systematic than the SEE-s observed previously at Tromso (Attachment 7).

ATTACHMENT 1

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# Observation of Suprathermal Electron Fluxes During Ionospheric Modification Experiments

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The temporal behavior of backscatter by ionospheric Langmuir waves was observed with the 430-MHz radar at Arecibo while a powerful HF wave was cycled 2 s on, 3 s off. The time resolution was 0.1 s. Late at night, in the absence of photoelectrons, using an HF equivalent radiated power of 80 MW at 3.175 MHz, the initial enhancement of about 6% above system noise of the backscattered power with Doppler shifts between −3.75 and −3.85 MHz was reached about 0.25 s after switching on the HF transmitter. In the following second the enhancement gradually decreased to about 3% and remained there until switching off. During the late afternoon, in the presence of photoelectrons, using the same HF power at 5.1 MHz, an initial enhancement by 25% of the backscattered power with Doppler shifts between −5.25 and −5.35 MHz appeared within less than 0.1 s after switching on the HF transmitter. The incoherent backscatter by Langmuir waves enhanced by photoelectrons was already above system noise by a factor greatly in excess of 10 before switching on the HF transmitter; the 25% enhancement thus corresponds to an enhancement greatly in excess of 250% above system noise. The enhancement drops to less than one tenth of its original value in less than a second. The nighttime effect is attributed to multiple acceleration of electrons from the high-energy tail of the Maxwellian distribution. The daytime effect is believed to be due to a modification in the distribution function of photoelectrons.

## 1. INTRODUCTION

The generation of enhanced airglow during the first ionospheric modification experiments at Platteville, Colorado [*Sipler and Biondi*, 1972; *Haslett and Megill*, 1974] was attributed to collisional excitation of the $O(^1D)$ and $O(^1S)$ states of atomic oxygen by suprathermal electrons. *Carlson et al.* [1982] reported the indirect detection of the suprathermal electrons by their enhancement of the very weak nighttime thermal plasma line of incoherent backscatter observed by the 430-MHz radar at Arecibo. Such an enhancement was predicted by the theory of *Perkins and Salpeter* [1965]. Although the enhancement was much weaker than that due to photoelectrons in daytime [*Yngvesson and Perkins*, 1968], the presence of electrons with energies at least up to 30 eV was verified. Direct verification of such electrons from a rocket was reported later by *Grandal et al.* [1983].

The present observations had the purpose of investigating the temporal variations of the plasma line enhancements as the HF transmitter was cycled 2 s on, 3 s off. Observations of this nature at night with a rather poor temporal resolution of 0.5 s were reported earlier by *Fejer et al.* [1985]. They found that the "cloud" of energetic electrons reached its full intensity some hundreds of milliseconds after the HF transmitter was switched on. The energetic electrons disappeared with a similar delay when the HF transmitter was switched off.

The present observations used an improved temporal resolution of 0.1 s and were carried out both at night and in daytime. In section 2 of this paper the theories of electron acceleration are reviewed briefly. In section 3 the nighttime observations in the absence of photoelectrons are described. Section 4 deals with the daytime observations, in the presence of photoelectrons Section 5 is devoted to the interpretation of the observations.

## 2. THEORIES OF ELECTRON ACCELERATION

The first quantitative theory of electron acceleration [*Weinstock*, 1975] applied resonance broadening theory [*Dupree*, 1966; *Weinstock*, 1968] to calculate the high-energy tail, due to parametric excitation, in the electron velocity distribution function. *Graham and Fejer* [1976] questioned the applicability of resonance-broadening theory to this type of calculation. *Graham and Fejer* [1976] suggested instead a single-step acceleration process by the parametrically excited Langmuir waves. They failed to point out, however, that such a single-step process could occur repeatedly as an electron collides with neutral particles and returns, perhaps several times, to the acceleration region. The importance of such a mechanism was pointed out by *Carlson et al.* [1982], who supported their arguments by detailed computations. *Gurevich et al.* [1985] have put such considerations of multiple acceleration into quantitative form; they also introduced the concept of acceleration by cavitons into their theory. They defined a caviton as "an arbitrary stationary or nonstationary density well filled up with intense electric field oscillations (Langmuir oscillations)."

The production of cavitons during ionospheric modification is very strongly suggested by the observations of *Birkmayer et al.* [1986], following earlier different types of observations by *Duncan and Sheerin* [1985] leading to similar suggestions. The cavitons appear in less than 10 ms



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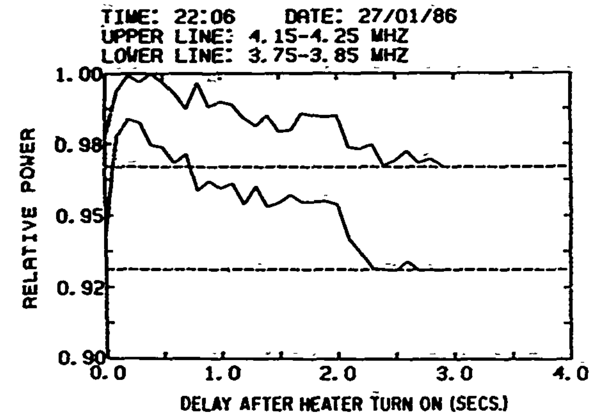


Fig. 1. Power in the natural plasma line in the absence of photoelectrons in two frequency bands as a function of time elapsed after the heater was turned on. The heater was turned off after 2 s. The ordinate scale is relative; only the fractional increase above the "noise level" (which includes a contribution from the galaxy as discussed in the text) is significant. The dashed lines were drawn to guide the eye and represent the "noise levels" in the two frequency bands. On the ordinate axis the lowest and highest values indicated are exact; the intermediate values have been rounded off to two decimals after interpolation.

[*Isham et al.*, 1987]. It seems therefore that the electrons are accelerated by the Langmuir waves inside cavitons.

A detailed discussion of cavitons and their properties is outside the scope of this paper. Quantitative comparisons of the present observational results with the theory of *Gurevich et al.* [1985] or with other theories will be left for a future publication.

## 3. Observations in the Absence of Photoelectrons

The observations described in this and the next section were carried out on January 20 and 27, 1986, at the Arecibo Observatory. The HF transmitter was at Islote, about 17 km northeast of the observatory; it radiated an equivalent power of 80 MW (400 kW with 23 dB antenna gain) toward the ionosphere. The HF transmitter was pulsed periodically 2 s on, 3 s off. Plasma line spectra were obtained over a bandwidth of 500 kHz by transmitting 430-MHz radar pulses of a length somewhat in excess of 1 ms and coherently sampling the backscatter from near the HF reflection height every 2 μs. The average of two spectra was written on tape every 100 ms. During the subsequent analysis, averaging over a very large number of 5-s cycles was carried out.

The observations described in this section were carried out at night, late enough for the disappearance of the effects of conjugate photoelectrons. Results for the time interval of about quarter of an hour, starting at 2206 UT on January 27, 1986, are shown by Figure 1. The frequency of the HF transmitter was 3.175 MHz. The choice of such a low HF was forced upon us by the solar minimum conditions and by the need to wait until the magnetically conjugate *F* region was no longer sunlit; by that time the maximum plasma frequency in the local *F* region sank to a low value. During the observations described by Figure 1, the maximum plasma frequency was about 4.4 MHz. Figure 1 shows the average temporal behavior of the relative power in the highest and lowest 100-kHz-wide bands of the 500-kHz-wide spectra with Doppler shifts of 3.75–4.25 MHz. The Doppler shifts are negative, that is, the downshifted plasma line was observed. The time resolution was 100 ms. The measured values are at the discontinuities in the slopes of the curves; the first measured value represents an average over the first 100 ms after switching on the HF transmitter.

Figure 1 shows that the enhancement of the plasma wave intensity is larger for the lower-frequency band of 3.75–3.85 MHz. The maximum enhancement is reached after about 0.25 s and is a little more than 6% of the system noise temperature (defined for our purpose as the sum of receiver noise temperature and galactic noise temperature, together about 120 K, the galactic component being variable). The enhancement drops to about half its maximum value after about a second and remains steady until the HF transmitter is switched off and the enhancement disappears in about 0.25 s. The observed finite rise and fall times of the enhancement are consistent with a multiple acceleration process [*Gurevich et al.*, 1985], during which an accelerated electron can return repeatedly to the acceleration region after collisional scattering. Eventually, a steady state is reached with energetic electrons distributed over a region extending considerably above and below the acceleration (interaction) region near the reflection height of the HF pump wave.

The maximum enhancement in the upper frequency band of 4.15–4.25 MHz is only about 4% of the system noise and is reached in a somewhat longer time of 0.45 s. Similarly, the enhancement disappears in a somewhat longer time of 0.35 s. This is not surprising because the height of the backscatter is further from the height of the acceleration region.

The energy of the electrons responsible for the scatter is greater than about 6.1 eV for the higher-frequency band and greater than about 5 eV for the lower-frequency band. These lower limits of energies are somewhat lower than those of 10–12 eV appropriate for the spectra of *Fejer et al.* [1985, Figure 10]. The lower energy limits were still higher for some of the observations described by *Carlson et al.* [1982], who incidentally also gave the explicit formula for the lower energy limit.

Observations made during the two quarter hour periods subsequent to the observations summarized by Figure 1 yielded essentially similar results and are not shown here. After 2250 UT, the maximum plasma frequency of the ionosphere sank to a value below which Langmuir waves of 35-cm wavelength are severely Landau damped [*Yngvesson and Perkins*, 1968] and therefore could not be used for the monitoring of energetic electrons.

## 4. Observations in the Presence of Photoelectrons

The experimental techniques used in the afternoon observations of January 20, 1986, and described in this section were identical to the techniques used in the nighttime observations described in section 3. The conditions of the observations are, however, radically altered by the presence of photoelectrons. It is well known [*Yngvesson and Perkins*, 1968] that the plasma line of incoherent backscatter is very greatly enhanced by the photoelectrons to levels which at Arecibo exceed the system noise by a factor considerably greater than 10.

Figure 2 shows the results of observations during about an hour starting at 1640:01 UT on January 20, 1986. Although the Langmuir waves excited parametrically close to the pump frequency of 5.1 MHz were outside the 5.25- to

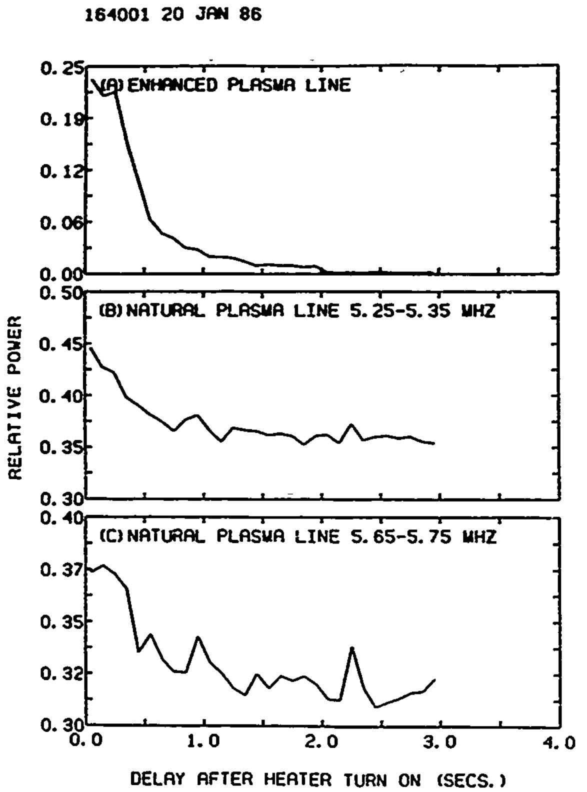


Fig. 2. Power in the aliased, enhanced plasma line and in the natural plasma line in the presence of photoelectrons in two frequency bands as a function of time elapsed after the heater was turned on. The heater was turned off after 2 s. The ordinate scales are relative; in Figures 2*b* and 2*c* only the ratios of the power levels existing during the first 2 s to the mean level during the 2.5- to 3-s time interval (not influenced by the heater) are significant. On the ordinate axes the lowest and highest values indicated are exact; the intermediate values have been rounded off to two decimals after interpolation.

5.75-MHz frequency band of the observations, the filtering was not sharp enough to prevent an aliased HF-enhanced plasma line to appear near 5.6 MHz. The difference of 0.5 MHz is the reciprocal of the sampling interval of 2 $\mu$s. Figure 2 therefore shows, in addition to the relative intensity of the backscatter with Doppler shifts of 5.25–5.35 MHz and 5.65–5.75 MHz, also the intensity of the aliased HF-enhanced plasma line with a Doppler shift near 5.6 MHz.

The aliased HF-enhanced plasma line shows the well-known overshoot phenomenon [*Showen and Kim*, 1978; *Djuth et al.*, 1986] and drops to about a twentieth of its original power in about a second. The natural plasma line enhanced by photoelectrons shows a strikingly similar behavior. This is especially true of the backscattered power with Doppler shifts of 5.25–5.35 MHz which shows an initial enhancement of about 25%. Since the photoelectron-enhanced natural plasma line exceeded the system noise by a factor considerably greater than 10, the previously mentioned 25% enhancement corresponds to enhancement considerably larger than 250% above the system noise. It does not seem possible that such a large enhancement, about 2 orders of magnitude greater than the nighttime enhancement, could result from the acceleration of electrons from the tail of the Maxwellian distribution. It is far more likely that the larger part of the effect results from a modification in the distribution function of the photoelectrons. It is true that the Langmuir waves can either accelerate or decelerate energetic electrons. However, the energy spectrum of photoelectrons is rather steep, and therefore more low-energy electrons will be accelerated than high-energy electrons decelerated.

The maximum power in the 5.25- to 5.35-MHz Doppler range is reached without a measurable delay according to Figure 2; the delay must therefore be less than 100 ms. Over the 5.65- to 5.75-MHz frequency range the peak power is reached with a measurable delay of the order of 100 ms. The maximum enhancement in power is about 20%.

Similar results to those of Figure 2 were obtained during 1640–1800 UT on January 27, 1986, over the 5.35- to 5.85-MHz Doppler frequency range. The enhancements observed were somewhat smaller; the results will not be shown here.

## 5. DISCUSSION

The results of the present observations show a distinct overshoot effect in the temporal behavior of the natural plasma line in the presence of energetic electrons when the HF transmitter is switched on. The present results differ in this respect from those shown by *Fejer et al.* [1985, Figure 10] which do not show an overshoot effect. The difference is believed to be due to the improved temporal resolution in the present experiments.

There is considerable uncertainty about the cause of the overshoot in the HF-enhanced plasma line at Arecibo. *Graham and Fejer* [1976] suggested that the overshoot is due to pump wave absorption caused by the growth of short-scale field-aligned irregularities within times of the order of a second. These irregularities are the product of a plasma instability [*Vaskov and Gurevich*, 1977; *Inhester*, 1982] in which the irregularity scatters the pump wave into Langmuir waves. The difficulty with the mechanism of *Graham and Fejer* [1976] is the lack of any measurable absorption in the reflected pump wave at 5.1 MHz and a simultaneous strong overshoot in the HF-enhanced plasma line during some of our as yet unpublished observations at Arecibo. The cause of the overshoot on such occasions is not yet known. The present results clearly demonstrate that the cause cannot be related to the development of the population of energetic electrons which could Landau damp the Langmuir waves. On the contrary, the overshoot appears to have a strong effect on the development of the population of energetic electrons at night and an even stronger effect on the changes in the distribution function of photoelectrons during the day, following the switching on of the HF transmitter. The delay of a quarter of a second or more during the nighttime observations is understandable qualitatively in terms of the multiple acceleration mechanism [*Gurevich et al.*, 1985]. The much shorter delays observed during the day can be understood in terms of a modification in the distribution function of photoelectrons which already had large energies before the HF transmitter was switched on. These shorter delay times also explain the larger overshoot effects observed in daytime.

A quantitative comparison with theory is not possible without theoretical calculations of the temporal and spatial development of the distribution function of energetic electrons after the powerful HF wave has appeared. It would be

very desirable to carry out such calculations in the near future.

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# Observational Limitations on the Role of Langmuir Cavitons in Ionospheric Modification Experiments at Arecibo

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**Observations of the time dependence of the enhanced plasma line power during high power ionospheric modification experiments at Arecibo, with a resolution of 1ms, sometimes showed 5-10 ms long pulses recurring very nearly periodically every 20-30 ms. Other observations of the slower variations of power at Arecibo show the gradual disappearance of the plasma line overshoot as the HF pulsing was changed from 0.5-s on 5.5-s off to 0.5-s on 19.5-s off, and its gradual reappearance as the pulsing was changed back to 0.5-s on, 5.5-s off. Observations of the height dependence of the enhanced plasma line spectrum were also made. They showed that the decay line with its cascade and the OTSI line all originated at the same narrow range of heights which observations by others showed to be near and just below the theoretical height of reflection of the pump wave rather than, as was previously believed, at the considerably lower height where the dispersion relation of the Langmuir waves detected by the radar is satisfied in the unperturbed medium. The possibility of interpretation of the observations in terms of existing theories is considered and the need for further theoretical and experimental work is pointed out.**

## 1. INTRODUCTION

Very soon after the start of ionospheric modification experiments [*Utlaut*, 1970] at Platteville, Colorado, Perkins and Kaw [1971] suggested that the electric field in the reflection region of the vertically incident HF modifying wave of ordinary polarization (the pump wave) at Platteville exceeded the threshold of certain parametric instabilities. *Wong and Taylor* [1971] and *Carlson et al.* [1972] demonstrated experimentally at the Arecibo Observatory by 430 MHz radar backscatter the parametric excitation of Langmuir waves. Subsequent experimental work at Arecibo [*Kantor*, 1974; *Duncan*, 1977] was interpreted in terms of the excitation of both the parametric decay instability (PDI) and the modulational or oscillating two-stream instability (OTSI), the latter as described by its linear dispersion relation. Both the HF modifying transmissions and the 430-MHz radar used the 305-m reflector in these early experiments.

*Fejer and Kuo* [1973a,b] and *Perkins at al.* [1974], extending the work *Kuo and Fejer* [1972] and *Kruer and Valeo* [1973] to more than one dimension, independently examined by means of weak turbulence theory a saturation mechanism for the PDI by a cascade of instabilities. In this cascade first the HF wave (the pump wave) decays into a Langmuir wave of slightly lower frequency and an ion acoustic wave by the PDI. The Langmuir wave then further decays and this decay process is repeated several times, resulting in a cascade of Langmuir waves of successively lower frequency, whose wave vectors form angles of less than about 25° with the pump electric field (which for the Arecibo experiment is very nearly parallel to the geomagnetic field). The theories also predict that the Arecibo radar (whose beam forms an angle of about 45° with the geomagnetic field) would not detect the unstable Langmuir waves directly; it would only detect the much weaker Langmuir waves which result from the scattering of the pump wave and of the cascade of unstable Langmuir waves by thermal ion acoustic waves. According to these theories there should be no sharp transition between radar backscatter spectra below and above threshold [*Fejer and Kuo*, 1973b; *Fejer and Sulzer*, 1984]. The predicted backscatter slightly above threshold would therefore be relatively weak although its power would increase as the square of the pump power within the range of validity of weak turbulence theory in a uniform medium. The theory in its one dimensional form [*Kuo and Fejer*, 1972] as extended by *Fejer and Kuo* [1973a] leads to a saturation spectrum that also includes the OTSI, i.e., the weak excitation of Langmuir waves at exactly the pump frequency; this aspect of the theory has not been extended to three dimensions.

Observations of 430-MHz radar backscatter spectra from Langmuir waves resulting from HF induced plasma instabilities, with frequencies near and slightly below the frequency of the pump wave (enhanced plasma line spectra) at Arecibo for different CW HF pump powers [*Fejer and Sulzer*, 1984; *Fejer et al.*, 1985, Figure 9] qualitatively confirm these predictions for pump powers below and slightly above threshold. It should be noted that the below threshold spectrum in Figure 9 of *Fejer et al.* [1985] has a peak spectral power density that is below the receiver noise level by about a factor of 4; the next weakest spectrum shown has a spectral power density that is above the noise level by a factor of about 10



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and has roughly the predicted spectral shape and intensity for a pump power density that is about 3 times above threshold. The noise level of about 100 K equivalent antenna temperature in those observations consisted of receiver noise and cosmic noise; it should be pointed out that in daytime the noise level can be greater than 1000 K and is mainly caused by backscatter from Langmuir waves Cerenkov-emitted by photoelectrons. The strongest spectrum of Figure 9 of *Fejer et al.* [1985] has a spectral power density that exceeds the receiver noise level by a factor of $1.3 \times 10^4$ and has a spectral shape that slightly resembles, against theoretical expectation, the cascade spectrum predicted by the weak turbulence theory of *Fejer and Kuo* [1973a,b] and of *Perkins et al.* [1974] for a radar beam parallel to the geomagnetic field. However, the power ratios of the cascade members are much greater than the theory predicts. The resemblance is even closer for the spectrum of Figure 2 of *Fejer et al.* [1985] obtained for an HF pump frequency of 3.175 MHz. At that frequency for Arecibo conditions the Landau damping of the Langmuir waves detected by the radar is rather high and this probably explains why the enhanced plasma line is present, if at all, for only a few hundred ms after the HF transmitter is switched on. During an on period of about half a second the electron temperature and therefore Landau damping rises to quench the instability for the Langmuir waves observable by the 430-MHz radar. An off period of about 10 s then allows the electron temperature to return to its original value and the process can be repeated. Entirely similar spectra have been obtained with similar pulsing of the HF transmitter operating at 5.1 MHz and will be discussed in section 5 of this paper.

The strongest spectra of Figure 9 of *Fejer et al.* [1985] cannot be explained by the theories of weak turbulence in a nearly uniform medium. Not only do they have the wrong spectral shape, but their peak spectral power densities are about 100 times higher than theoretically predicted on the basis of reasonable estimates of pump electric fields.

Equations governing strong Langmuir turbulence (SLT) were formulated by *Zakharov* [1972] and were used in many numerical simulations since then. *Zakharov* [1972] also discussed his equations analytically and showed that a monochromatic Langmuir wave of sufficient amplitude is unstable to the formation of a very large number of Langmuir cavitons (localized density depletions filled with Langmuir oscillations) which in the course of time become more and more localized (collapse) until eventually the Langmuir waves are dissipated by Landau damping (burnout). Recent numerical simulations based on the Zakharov equations [*Russell et al.*, 1986, 1988] demonstrated this process and also showed that after caviton collapse and burnout a new caviton is formed at the place of the old burnt-out caviton, thus leading to a locally quasi-periodic process.

The above brief account does not do justice to the extensive literature on Langmuir cavitons/solitons. A few among the works omitted are the laboratory experiments agreeing with numerical simulations, described by *Wong and Cheung* [1984] and *Tanikawa et al.* [1984] and the theoretical work of Morales and Lee [1977].

*Petviashvili* [1976] suggested that cavitons must form in ionospheric modification experiments using a powerful HF pump wave with ordinary polarization. *Weatherall et al.* [1982] confirmed by numerical simulations based on the Zakharov equations the suggestion of *Petviashvili* [1976] that pancake-shaped cavitons are formed with the "planes" of the "pancakes" perpendicular to the magnetic field.

The first observations that could have possibly been interpreted as indirect evidence for the formation of ionospheric cavitons were made by *Muldrew and Showen* [1977] although they did not interpret their own observations in terms of cavitons. They found that the enhanced plasma line came from a height that was greater by a few kilometers than the height of the natural plasma line (mainly the backscatter from Langmuir waves Cerenkov emitted by photoelectrons in daytime as mentioned earlier). They explained these observations in terms of isolated field-aligned plasma density depletions or ducts, inside which the dispersion relation of Langmuir waves can be satisfied near the reflection height of the HF wave. This interpretation was further developed by *Rypdal and Cragin* [1979]. In addition to explaining the height observations of *Muldrew and Showen* [1977], the duct hypothesis also explains the observed strong plasma line spectra; the medium is no longer uniform and therefore the weak turbulence theory in a uniform medium, as formulated by *Fejer and Kuo* [1973a,b] and by *Perkins et al.* [1974], is not applicable and must be replaced by the theory of *Rypdal and Cragin* [1979] which at least qualitatively explains the observations.

*Birkmayer et al.* [1986] and *Isham et al.* [1987] confirmed the experimental results of *Muldrew and Showen* [1977] by an elegant and entirely different experiment using chirped radar pulses [*Hagfors*, 1982]. They interpreted their results, however, in terms of the excitation of Langmuir cavitons near the reflection height of the HF wave rather than in terms of field-aligned ducts. This was also the interpretation by *Duncan and Sheerin* [1985] of their own observation of an increase in the height of the enhanced plasma line echo within a few milliseconds after switching on the HF transmitter.

A modification of the ionospheric density profile and the creation of a density depression at the critical height by a high power radio wave was observed at Arecibo by *Wong et al.* [1987]. They used the photoelectron enhanced plasma line for the measurement of the ionospheric density profile and noted the suppression of the intensity of that line at the critical height. They attributed this suppression to small-scale Langmuir cavitons imbedded in the larger-scale density depression.

The primary purpose of the present paper is the presentation of some new experimental results.

Section 2 describes some observations of fast temporal variations (including some surprising periodicities) of the power in the enhanced plasma line, with a resolution of 1 ms.

Section 3 describes observations of the plasma line overshoot [*Showen and Kim*, 1978] obtained by the same technique.

Section 4 presents observations of the height-dependence of the enhanced plasma line spectrum with CW heating.

Section 5 presents observations of the height dependence of the enhanced plasma line spectrum with pulsed heating.

Section 6 presents observations of the spectral width of the OTSI line and of the dependence of that width on the strength of the pump electric field.

Section 7 is devoted to the detailed interpretation of the observational results. In the earlier sections interpretation is kept to a minimum.

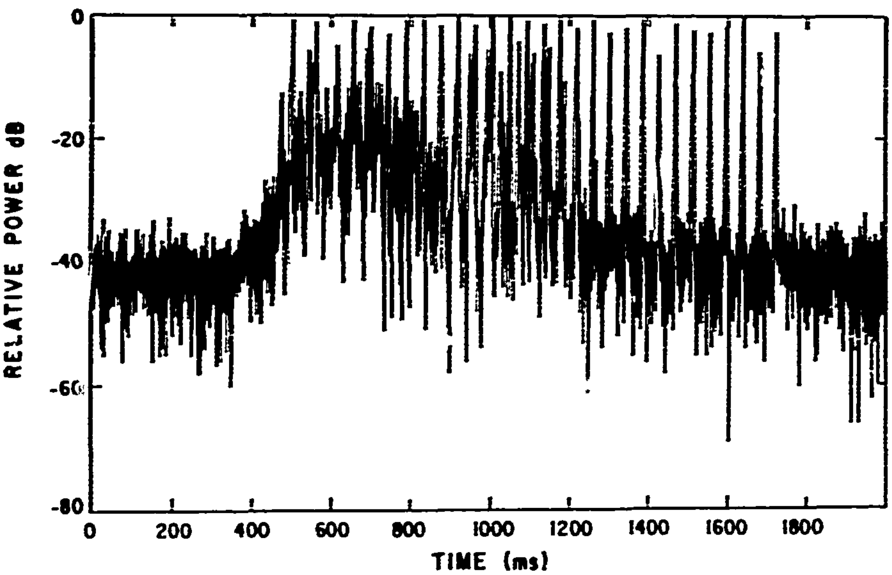


Fig. 1. Quasi-periodically recurring pulses in the relative power in decibels of the enhanced plasma line with a 2-s on, 2-s off transmitting sequence, sampling the power every millisecond. A 2-s long period starting at 1632:09 on January 19, 1987 is displayed.

## 2. FAST TEMPORAL VARIATIONS IN ENHANCED PLASMA LINE POWER

The motivation for the observations described in this section was the finding by *Fejer et al.* [1985], based on the visual inspection of the enhanced plasma line echo on a radar A scan, that the temporal behavior of the total power in the weak broad and in the strong narrow spectra of their Figure 9 was very different.

During the present observations, 430 MHz radar pulses were transmitted with an interpulse period (IPP) of 1 ms. The power in the enhanced plasma line was therefore recorded with a temporal resolution of 1 ms. Figure 1 shows a 2-s-long record of the enhanced plasma line echo power, starting at 1632:09 on January 19, 1987. The HF transmissions from Islote, about 17 miles northeast of the observatory had an equivalent radiated power of 40 MW at 5.1 MHz and were cycled 2-s on, 2-s off. Ordinary polarization was used. The HF transmissions were started shortly after the 400 ms mark on Figure 1. The enhanced plasma line in Figure 1 is only seen during the overshoot and disappears shortly after the 1600 ms mark. During the last 500 ms before its disappearance practically all the power in the enhanced plasma line is in nearly perfectly periodically recurring pulses of somewhat less than 10 ms duration, with an IPP of about 42 ms.

Figure 2 shows the first 200 of 1024 values in the digital power spectrum of the plasma line echo power in the 600 ms to 1623 ms time interval of Figure 1. Most of the power is clearly in the periodically recurring pulses. There were many other examples of records similar to that shown by Figure 1 during the same afternoon although they were not

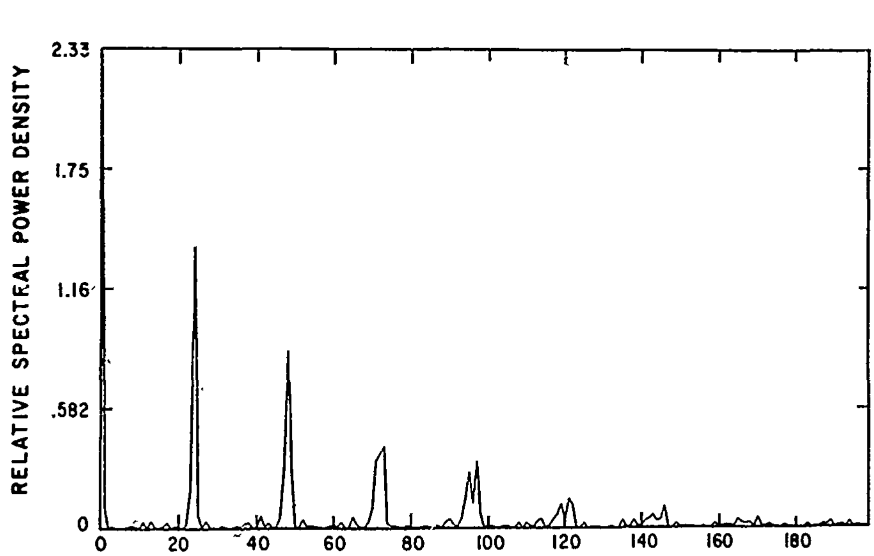


Fig. 2. The first 200 values of the digital power spectrum of the 1024 sample values a millisecond apart of the enhanced plasma line power shown by Figure 1, starting at the 600-ms mark.

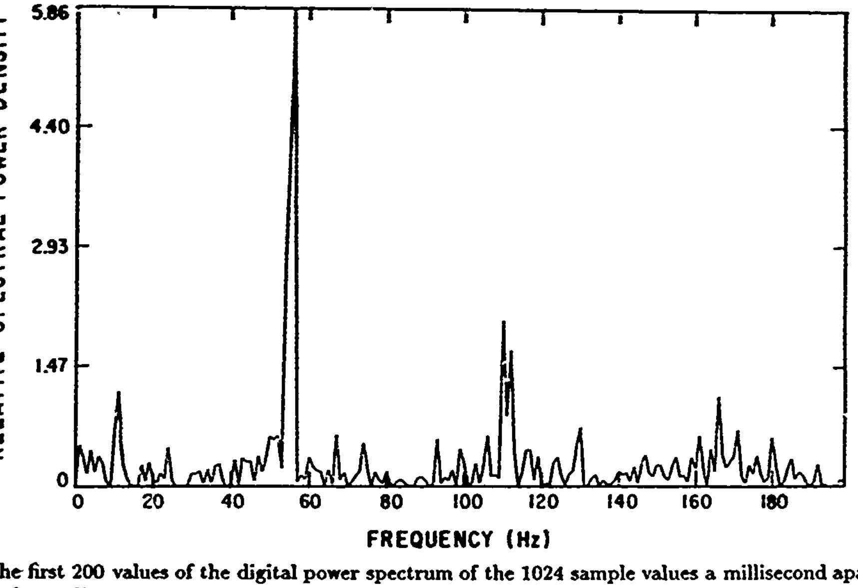


Fig. 3. The first 200 values of the digital power spectrum of the 1024 sample values a millisecond apart of the enhanced plasma line power, with a 15-s on, 45-s off transmitting sequence. Sampling started at 1657:16 on January 20, 1987, about 3-s before the end of a 15-s on period.

typical. For example a record starting at 1651:55, not shown here, showed almost periodically recurring pulses with the IPP varying between 33 ms and 48 ms, with correspondingly broader spectral peaks.

During the next afternoon, on January 20, 1987, similar observations were carried out using the same frequency and ERP with a pulsing cycle of 15 s on, 45 s off; the same cycle was used in the experiment of *Birkmayer et al.* [1986]. Conditions near the end of a 15 s on period must have resembled those under CW operation. Figure 3 shows the first 200 values of the power spectrum for the 1024 ms long period starting at 1657:16, just 3 s before the end of a 15 s on period. The period derived from the spectrum is about 18 ms. Very similar spectra were obtained for four of the last five 1024 ms long periods of the 15 s on period.

Summing up, clear periodicities such as shown by the spectra of Figures 2 and 3 are often seen. At other times the spectra do not show clear periodicities although they do not resemble random noise. An example is shown by the spectrum of Figure 4, for the first 1024 ms of an earlier 15 s on-period at 1655:05 on January 20, 1987. Figure 4 shows the entire spectrum; only the first 512 values are displayed on account of the symmetry in the power spectrum of a real function. At still other times the spectrum resembles that of random noise; the spectrum of Figure 5, obtained 6 s later at 1655:11, is an example. Apart from the very much larger spectral power densities, the spectrum of Figure 5 is indistinguishable from the spectrum of receiver noise obtained by the same technique in the absence of HF transmissions and not shown here. The reader is reminded that if the process

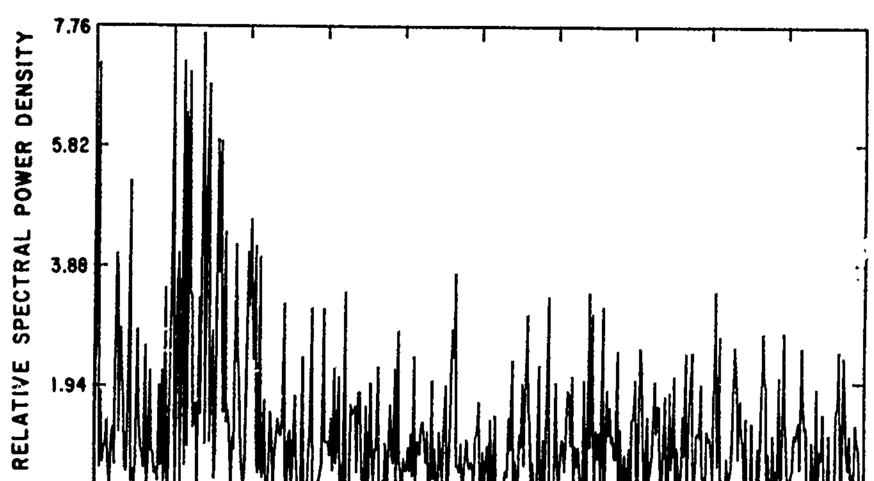


Fig. 4. The first 512 values of the digital power spectrum of the 1024 sample values a millisecond apart of the enhanced plasma line power, with a 15-s on, 45-s off transmitting sequence. The sampling started at 1655:05 on January 20, 1987 at the beginning of a 15-s on period.

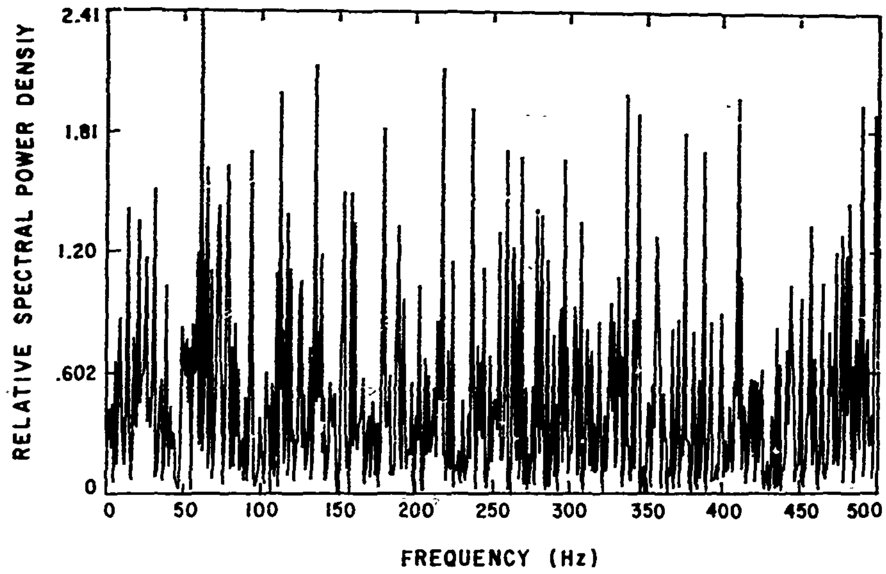


Fig. 5. The first 512 values of the digital power spectrum of the 1024 sample values a millisecond apart of the enhanced plasma line power. The sampling started at 1655:11 on January 20, 1987, 6 seconds later than in Figure 4.

generating the enhanced plasma line were stationary and random, then a spectrum resembling that of random noise would be expected.

## 3. The Overshoot in the Enhanced Plasma Line

*Showen and Kim* [1978] first pointed out that the power in the enhanced plasma line usually reaches a maximum rather fast after switching on the HF transmitter. After a time of the order of a second the power usually drops to a lower value and then no longer decreases systematically. Occasionally, the enhanced plasma line is only present during the over-shoot; for a pump frequency of 3.175 MHz at Arecibo this is always the case and can be explained in terms of increased Landau damping, caused by a rise in electron temperature, of Langmuir waves of 35-cm wavelength detected by the 430-MHz radar. For higher pump frequencies like 5.1 MHz the Landau damping of the Langmuir waves detected by the 430-MHz radar is insignificant; an explanation of the overshoot for that case in terms of the development of short-scale field-aligned irregularities within about a second was proposed by *Graham and Fejer* [1976]. They suggested that the pump wave is scattered by the irregularities into Langmuir waves; the resulting absorption of the pump wave is the cause of the overshoot. This explanation is questioned by *Djuth et al.* [1986] who estimate that less the 10% of the power in the reflected 5.1 MHz heating wave is absorbed due to the excitation of Langmuir waves; this clearly can not ex-

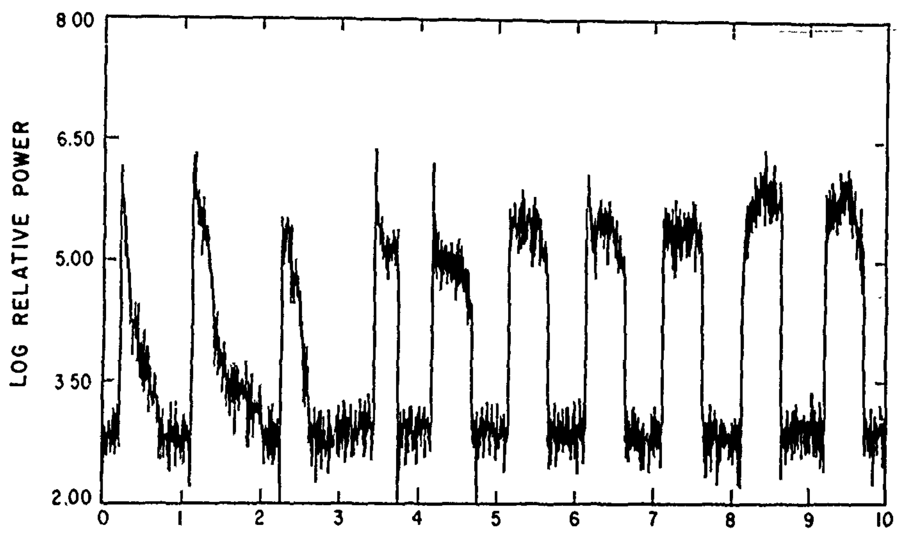


Fig. 6. The logarithm of the power in the enhanced plasma line as a function of time. The data are displayed only near the 0.5-s on periods, starting 2015:49 on 19 January, 1987 when the HF transmission sequence was changed from 0.5-s on, 5.5-s off to 0.5-s on, 19.5-s off. As a result of the nature of the data taking program, the beginning of the third and the end of the fourth 0.5-s on periods were not recorded.

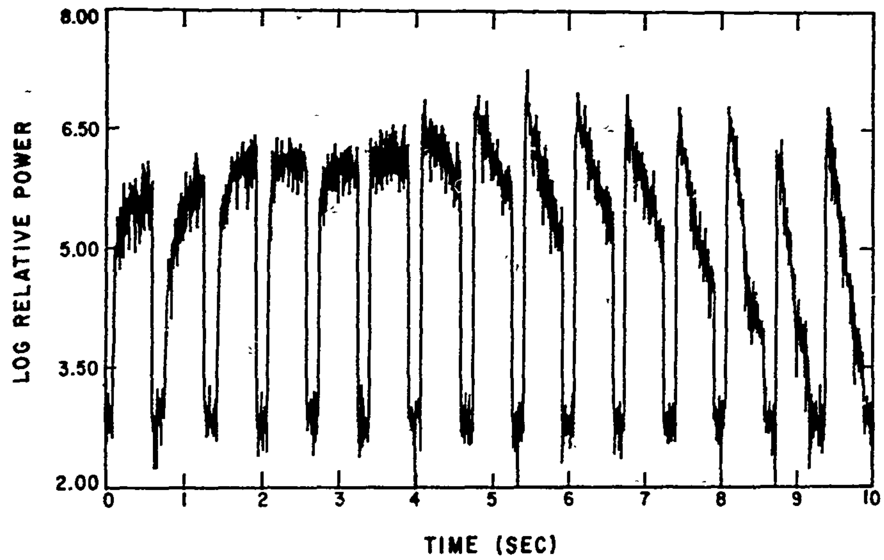


Fig. 7. The logarithm of the power in the enhanced plasma line as a function of time. The data are displayed only near the 0.5 s on periods, starting 2027:26 on January 19, 1987 when the HF transmission sequence was changed from 0.5-s on, 19.5-s off to 0.5-s on, 5.5-s off.

plain the observed strong overshoots. A possible alternative explanation [*Muldrew*, 1988a] will be discussed in the last section.

The overshoot phenomenon discussed in this section is different from some other very interesting and important effects related to pulsing the HF transmitter and described by *Morales et al.* [1982].

It should be remarked here that the short-scale field-aligned irregularities are much more intense and play a far greater role at higher latitudes where more than 90% (rather than sometimes less than 10% as at Arecibo) of a reflected heating wave near 5 MHz is absorbed [*Fejer and Kopka*, 1981] as a result of scattering by the field-aligned irregularities into Langmuir waves. The reason for this different behavior is that the scattering process (and the thermal parametric instability generating the irregularities that will be discussed shortly) depends on that component of the pump electric field which is perpendicular to the geomagnetic field; the strength of the perpendicular component is far greater at higher latitudes than at Arecibo. This incidentally explains the much greater stress in the recent Soviet literature on the thermal parametric instability [*Vaskov and Gurevich*, 1975; *Grach et al.* 1977; *Das and Fejer*, 1979; *Inhester*, 1982] responsible for the short-scale field-aligned irregularities than on the ponderomotive type parametric instabilities responsible for the enhanced plasma line at Arecibo.

The observations described in this section are believed to shed further light on the nature of the overshoot. Figures 6 and 7 show the logarithm of the power of the enhanced plasma line as a function of time. Each point in Figures 6 and 7 shows the average of 5 successive values of the power written on tape every millisecond as in the last section. Figures 6 and 7 describe the temporal evolution of the power in the enhanced plasma line while the pulsing sequence of the HF transmitter was changed from 0.5-s on, 5.5-s off to 0.5-s on 19.5-s off at 2015:49 on January 19 1987, and was changed back to 0.5-s on, 5.5-s off at 2027:26. Only the immediate temporal vicinities of the 0.5-s on periods are shown by the Figures. Figure 6 shows 10 on periods after 2015:49 and indicates the gradual disappearance of the strong overshoot during about two minutes. Similarly, Figure 7 shows the gradual reappearance of the overshoot in about 1.5 min.

## 4. Height-Dependence of the Enhanced Plasma Line Spectrum for CW Heating

### 4.1 Observational Technique

The technique used for obtaining simultaneous spectra from several heights with the Arecibo 430 MHz radar was that of coded long pulses [*Sulzer*, 1986]. This technique has certain advantages over the multiple pulse technique [*Farley*, 1972] for radars using klystrons in which the beam current has to be kept flowing between the pulses of the multiple pulse technique.

A previous application of the technique of coded long pulses was described by *Fejer et al.* [1985]. Their Figure 4 shows the spectra observed by that method. A pulse of about 1 ms was randomly phase coded with a baud of 8 μsec length. The random phase code was changed often enough to ensure that a strong almost monochromatic signal coming from one height appears as random noise (usually called clutter) at any other height. A spectrum was obtained after an integration time of about one minute. The results were interpreted in terms of fading resulting from self-focusing. Spectra corresponding to below threshold conditions were obtained from a lower height and strong spectra from a greater height.

In the present work it was attempted to eliminate the effects of fading by integrating at first over periods of only about 5-s length during which the code was changed 3 times. These 5-s long 'records' contained six spectra for six different ranges 1.2 km apart. They were written on tape and were displayed for "quick look". In the next section such 5-s-long records will be used directly. In this section a long sequence of 5-s-long records was subsequently analyzed by computer. Only 'records' with a strong plasma line were retained (about a quarter of the records were rejected by

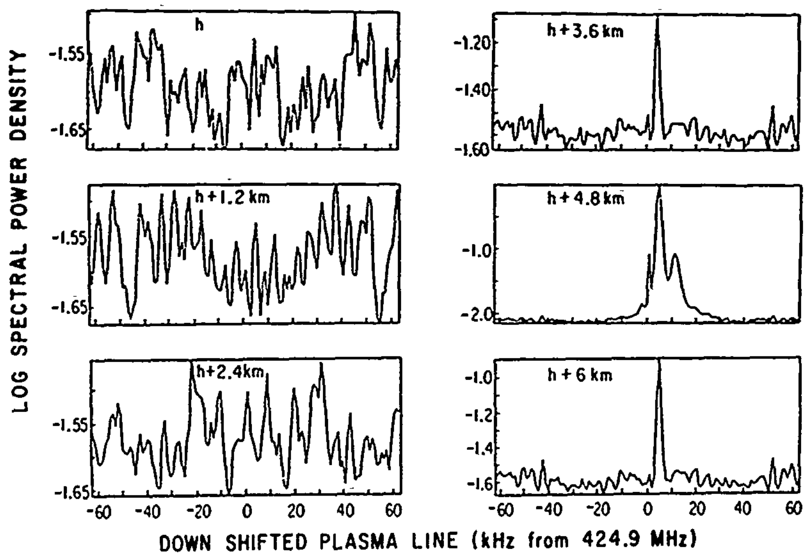


Fig. 8. The spectrum of the downshifted enhanced plasma line for the 15 minute period starting 1750 on January 24, 1986, for six different "heights" 1.2 km apart as explained in the body of the paper.

the computer). The spectrum with the strongest peak of a retained 'record' was then placed for accumulation in the second highest of six range bins covering a height range of 7.2 km; the other spectra of the 'record' were placed for accumulation into corresponding range bins, when such were available. During the observations the starting time of the decoding sequence was occasionally adjusted in order to keep the strongest spectral peak in one of the three highest ranges of the quick-look display. On transferring the spectra of a "record" to the range bins of the analysis program therefore the spectra in some range bins received no addition and for some spectra of the "record" there was no range bin available.

The procedure just described was designed to get rid of the effects of fading and of slow changes in the ionosphere; the range bins were meant to indicate the height relative to the height of the strongest spectrum rather than absolute height. Typically the power spectra of about hundred "records" were accumulated in this manner by the analysis program, representing about 10-15 min of observation time.

As described by *Sulzer* [1986], the noise level will be lowest in that spectrum of a "record" which contains the strongest spectral peak, on the assumption that an almost monochromatic strong spectrum is produced at only one height and this height is exactly matched by the decoding for one of the ranges of the "record". Then the monochromatic signal power coming from that height is converted into random noise (called clutter) for the other five height ranges of the "record".

The six spectra shown by Figure 4 of *Fejer et al.* [1985] show practically the same noise level for all height ranges. The reason for this is that in those spectra the plasma line power exceeds the noise by a factor considerably smaller than 128, the number of points in the digital Fourier transform. This will not be the case in the spectra obtained in the present observations in which the maximum spectral power density can exceed the noise level by a factor comparable to or even greater than 128, the number of points in the FFT used. Moreover, in the present analysis program an unequal number of spectra were accumulated in the six range bins and this could also have caused differences in the noise level if the sums of the spectra had been displayed. It was therefore decided to display the average spectrum rather than the sum.

*4.2. Results Of The Observations*

The observations took place on January 21 and 24, 1986, in the late afternoon. An equivalent radiated power (ERP) of 80 MW at a frequency of 5.1 MHz in the continuous wave (CW) mode was used. The spectra averaged over different quarter hour periods differed little and therefore only one of them will be shown here. Figure 8 for the period starting at 1750 AST on January 24 shows a typical set of spectra.

Before looking at those spectra in detail it should be noted that the noise level in the second highest range bin at the center on the right is 2-3 times lower than the noise level in the other range bins. It was explained in section 4.1 that this is an expected property of the coded long pulse technique.

It should also be noted that the noise level is not only higher in the other range bins but the relative fluctuations in the noise are about three times larger than in the second highest range bin although the same integration time has been used for all the bins. This is believed to have been caused by using a random number sequence for the phase code which was periodic with too short a period. This minor shortcoming will be rectified in future observations using this technique.

Turning to the spectra of Figure 8, the largest spectral peak occurs at the frequency expected for backscatter from Langmuir waves of the parametric decay instability. The peak spectral power density is on the average about 10 times higher in the second highest range bin than in the two neighboring range bins (top and bottom on the right) in Figure 8. It is shown in the Appendix that if all the scatter came from a single height then this ratio would have the value of 14 rather than 10. The observed average ratio of 10 implies according to the appendix that the scatter comes from a height range of about $\pm$ 0.53 km. The considerations of the Appendix were based on the assumption that the height of

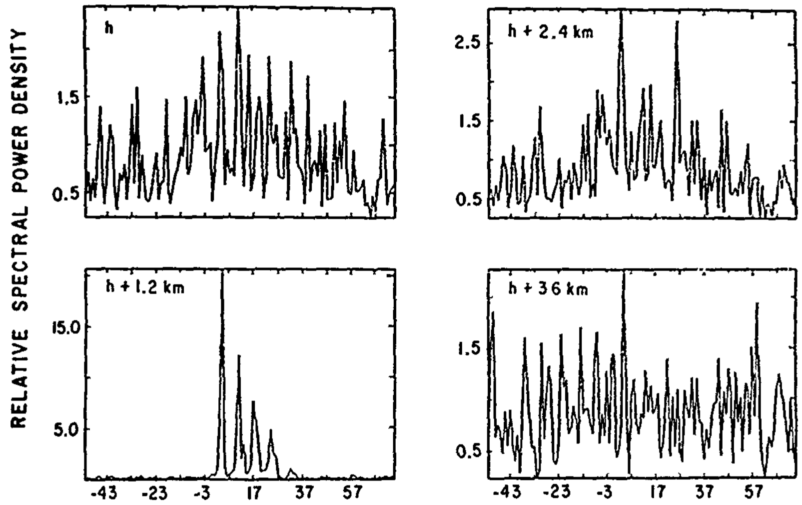


Fig. 9. The spectrum of the downshifted enhanced plasma line for the 5-s long period starting 1654.27 on January 21, 1987, for four different heights 1.2 km apart.

scattering varied over a considerably larger range than 1.2 km during the quarter hour integration period. Records of the height of scattering justified that assumption. The fact that the above ratio was between 8 and 10 for most of the spectra observed on January 21 and between 6 and 8 on January 24, also makes the considerations of the appendix seem realistic.

Besides the most prominent spectral feature already mentioned, the so called decay line, there are two other much weaker but nevertheless quite prominent spectral features. One of these has a Doppler shift exactly equal to the pump frequency. It is believed to result from backscatter by the Langmuir waves of the OTSI. The other weaker feature is the product of a second parametric decay process in which Langmuir waves of the original parametric decay instability decay further parametrically into Langmuir waves traveling in the opposite direction and into ion acoustic waves with roughly twice the wave number of the Langmuir waves. Therefore the frequency spacing between this feature and the decay line is twice the frequency spacing between the decay line and the OTSI (on the other side of the decay line in the spectrum).

In Figure 8 these two weaker features are shown most clearly by the spectrum in the second highest range bin. They may also be discerned weakly in the spectra of the two neighboring range bins. It is significant that these weaker features have an intensity in the two neighboring range bins that is estimated to be about one tenth of their intensity in the second highest range bin. Thus the weaker spectral features appear to come from approximately the same height range as the strong decay line feature.

Another still weaker spectral feature of the second highest range bin in Figure 8 is the anti-Stokes line whose Doppler shift is larger than that of the OTSI line by the same amount by which the Doppler shift of the decay line is smaller. Other still weaker features are the higher-order members of the cascade.

The spectra of the lowest three range bins only contain noiselike clutter. There is no sign of a plasma line spectrum backscattered from a lower height where the dispersion relation of Langmuir waves would be satisfied in the unperturbed medium. A possible explanation is that the spectrum from the lower height was masked by the high level of clutter resulting from the very strong signals in the second highest range bin.

These observations lead to the conclusion that the HF enhanced plasma line is produced by backscatter from a height range whose width is typically about 1 km. The observations also show that the decay line, its cascade, and the OTSI line all come from roughly the same height range.

The results of the present observations, combined with the results obtained by *Birkmayer et al.* [1986], show that, for high pump powers, the HF enhanced plasma line including the decay line, a weak cascade, and the OTSI line, are all scattered from roughly the same range of heights which is well above the height where the dispersion relation is satisfied in the ambient medium.

It must be stressed here that the terms "decay line," "weak cascade" and "OTSI line" are current Arecibo parlance which has its origin in the assumption that parametric instabilities are associated with these spectral features. We do not imply by using these terms the exclusion of other possible interpretations of these spectral features.

## 5. HEIGHT-DEPENDENCE OF THE ENHANCED PLASMA LINE SPECTRUM FOR PULSED HEATING

*Djuth et al.* [1986] showed that for pulsed heating with a high duty cycle such as 170 ms on 30 ms off, a spectrum resembling the strongest spectra of Figure 9 of *Fejer et al.* [1985], obtained by CW heating, is established within a few milliseconds after switching on the heater (their Figure 3). If on the other hand a low duty cycle such as 350 ms on 1650 ms off is used then the spectrum generally remains broad and strong during the overshoot (for about 80 ms for the upshifted plasma line in their Figure 12).

In the work described here, plasma line spectra were obtained in January 1987 by the coded long pulse method with a 100 ms on, 1-s off heater cycle. The spectra were

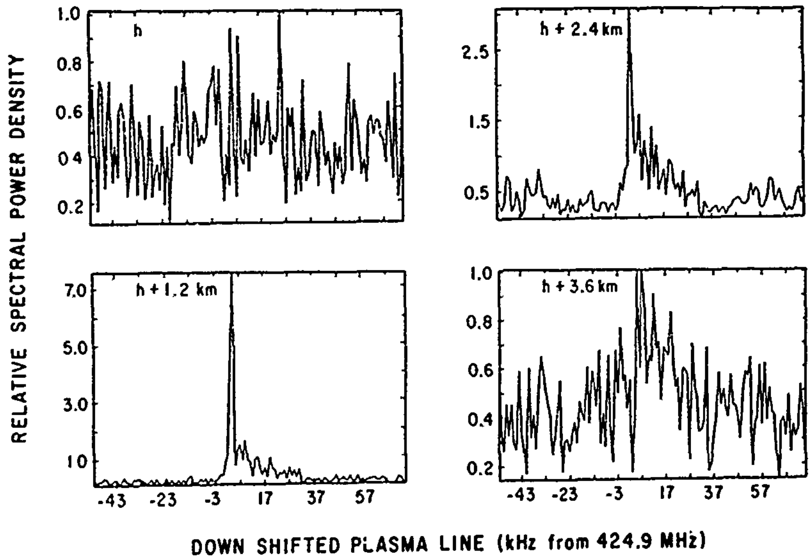


Fig. 10. The spectrum of the downshifted enhanced plasma line for the 5-s long period starting 1750:40 on January 21, 1987, for four different heights 1.2 km apart.

obtained over periods of about 5-s length during which the code was changed three times.

Figure 9 shows spectra at 4 heights 1.2 km apart for 5.1-MHz heating with 40 MW ERP. A reasonably strong plasma line spectrum is only seen at the second lowest height (bottom left); it strongly resembles the spectrum of Figure 2 of *Fejer et al.* [1985] which was obtained by Duncan and Sulzer for a heating frequency of 3.175 MHz. More commonly, the spectra observed by us do not resemble the spectrum of Figure 2 of *Fejer et al.* [1985] but are broader than the spectrum of Figure 8. Examples are Figure 10, obtained with 5.1 MHz heating, and Figure 11, obtained with 4.438 MHz heating. Figure 11 was traced from a hard copy of the quick-look display; inadvertently, the tape recording was not functioning at the time. Figures 10 and 11 illustrate that there is a weak height dependence of the spectrum; the spectrum with the wider spread may occur at the greater height as in Figure 10, or at the smaller height as in Figure 11.

## 6. THE WIDTH OF THE OTSI LINE

The technique of using short radar pulses with an IPP of 1 ms for the study of narrow spectral features in the enhanced plasma line was described by *Sulzer et al.* [1984]. During July 1984 the spectrum of the OTSI line was studied extensively by this technique. Spectra of 1-kHz width were thus obtained in which the aliased decay line and its cascade appear as noise on account of their large bandwidth. The OTSI line on account of its narrowness is usually clearly seen in the 1-kHz wide spectra. Theoretically, in the absence of ionospheric drifts, the frequency of the OTSI line should differ from the radar frequency of 430 MHz by the pump frequency of 5.1 MHz, used in the observations to be described in this section.

Figure 12 shows several such 1-kHz wide spectra as the power radiated by the HF transmitter was changed once a minute, alternating between 20 MW and 40 MW ERP, corresponding 4x25 kW and 4x50 kW being fed into the antenna system of 23 DB gain. The frequency of the upshifted OTSI line shown by Figure 12 differs by about 100 Hz less than the pump frequency from the radar frequency. This implies a line of sight component of the drift velocity of the electron gas of 35 m/s.

The most noteworthy feature of the spectra shown is the decrease in the half-power width of the OTSI line every time when the HF power was decreased and the increase in the half-power width every time when the HF power was increased. The peak at 0 Hz is instrumental and should be ignored.

The observations had an even more noteworthy feature, not displayed by Figure 12. When the power was increased

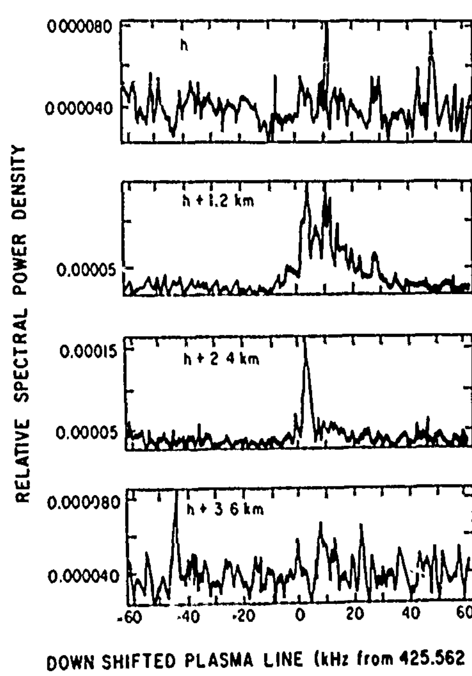


Fig. 11. The spectrum of the downshifted enhanced plasma line fo the 5-s long period starting at about 2127 on January 20, 1987, for four different heights 1.2 km apart.

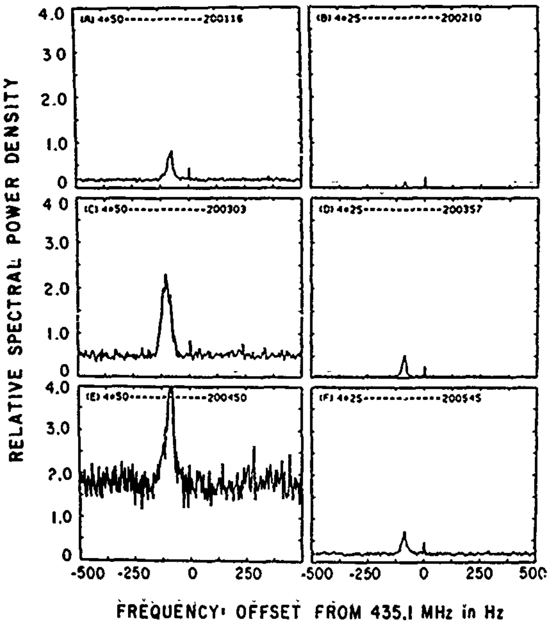


Fig. 12. Spectra of the OTSI line obtained in the evening of July 30, 1984. The transmitted HF power was alternating between 4x25 kW and 4x50 kW. Most of the spectral power is in the aliased PDI line which appears as noise on account of its wider bandwidth.

to 4x100 kW, the OTSI line usually could not be discerned in the spectrum. This was probably caused by a further large increase in the width of the OTSI line, making it undetectable by the technique used.

On time scales longer than a minute, self-focusing reduces the correlation between the HF power transmitted and the HF field in the ionosphere. This lack of correlation is shown by the steady increase with time of the power (the area under the curve) in the enhanced plasma line for both 4x50 kW and 4x25 kW. Most of the power is clearly in the decay line, especially for higher transmitted powers. It seems therefore that the total power in the enhanced plasma line is probably a better indication of pump power density in the ionosphere than the power transmitted from the ground. Figure 13 shows the bandwidth of the OTSI line as a function of the logarithm of the total power in the enhanced plasma line, on a relative scale, for 42 one minute long observations that showed a clearly discernible OTSI line. The correlation coefficient is 0.67. Although this is not a very high value, it confirms the positive correlation suggested by Figures 12 and 13 between the bandwidth of the OTSI line and the pump power.

## 7. CONCLUSIONS

It was already demonstrated before the present observations by *Birkmayer et al.* [1986], confirming earlier related observational results of *Muldrew and Showen* [1977] and of *Duncan and Sheerin* [1985], that the enhanced plasma line at Arecibo is the result of backscatter by Langmuir waves from near the height of reflection of the pump wave and not from the lower height where the dispersion relation of Langmuir waves is satisfied in the unperturbed plasma.

The present observations of temporal periodicities in the enhanced plasma line power may seem to agree superficially with the results of numerical simulations of periodically collapsing Langmuir cavitons at Los Alamos in one dimension [*Russell et al.*, 1986] and in two dimensions [*Russell et al.*, 1988]. However,it has been pointed out to one of the present authors (J.A.F.) by D. F. DuBois (private communication, 1987) that there are serious obstacles in the way of such an interpretation. An attempt to describe these obstacles follows.

The numerical simulations at Los Alamos [*Russell et al.* 1986, 1988] show that the cavitons would have dimensions of the order of 5-50 cm [*DuBois et al.*, 1988] for typical ionospheric parameters, and that the period of the collapse-

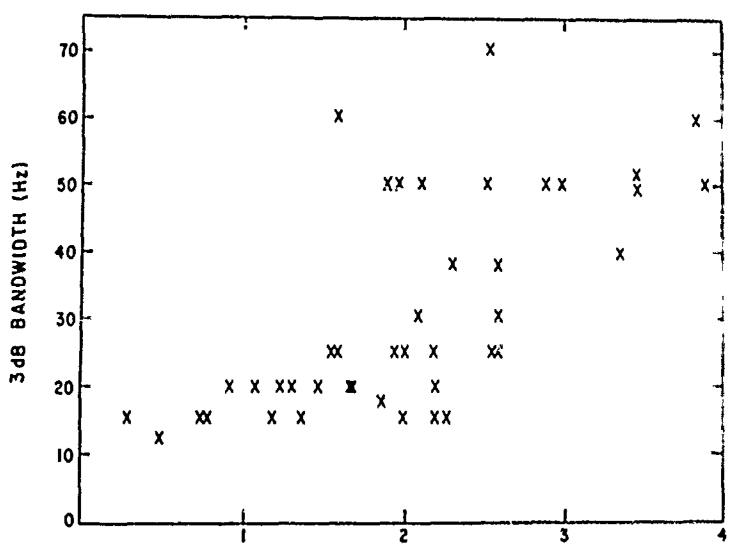


Fig. 13. The half-power bandwidth of the OTSI line as a function of the logarithm of the relative total power in the enhanced plasma line. The observations took place in the evening of July 30, 1984. Only those 42 spectra were used which clearly showed the OTSI line; this eliminated spectra with wider bandwidths of the OTSI line than 100 Hz.

regrowth process would be less than 1 ms rather than the 20-50 ms observed. Moreover, the number of cavitons responsible for the radar backscatter would be of the order of $10^7$, and there is no reason to believe that they would be correlated and thus collapse synchronously, even if the period of the collapse-regrowth process were longer. These obstacles are only in the way of explaining the observed 20-50 ms periodicities in the enhanced plasma line power; as will be seen shortly, some aspects of the observed spectra appear to be in agreement with the results of the simulations.

The physical nature of the collapsing cavitons of the simulations is characterized by its complete independence from the pump during the collapse; the collapsing caviton simply accommodates plasma oscillations at the changing resonance frequency of its trapped Langmuir mode until the oscillations are dissipated by Landau damping (burnout). After burnout the cavity relaxes thermally until its Langmuir resonance frequency approaches the pump frequency (nucleation). Forced oscillations are then excited near the pump frequency, the collapse starts again and the process repeats itself. Parametric processes play no part in this plasma turbulence after the initial stage [*DuBois et al.*, 1988].

In contrast to this physical process characterizing the simulations, the stronger ionospheric spectra of radar backscatter from Langmuir waves of 35 cm wavelength (the so-called enhanced plasma line), as shown for example by Figure 8 for the second greatest height, display at least some signs of the excitation of the parametric decay instability and its weak cascade, as well as the weak excitation of the OTSI. As pointed out earlier, however, those spectra disagree with the predictions of weak turbulence theory in a uniform medium. Attempts to resolve these disagreements were made by postulating the existence of field aligned depletions in the plasma density with transverse dimensions of the order of tens of meters [*Muldrew and Showen*, 1977, *Rypdal and Cragin*, 1979]. These attempts were mentioned in the introduction in connection with the explanation of the height of 430-MHz radar backscatter. Further attempts along similar lines will be mentioned later.

A completely different interpretation of the observed spectra is suggested by *DuBois et al.* [1988] in terms of the strong Langmuir turbulence (SLT) model of *Russell et al.* [1986, 1988] originally proposed by Zakharov (1972). *Du Bois et al.* [1988] conclude that the turbulent stationary state is modulationally stable and that, as mentioned earlier, parametric instabilities play no role in it except for the possible role of initiation. Surprisingly, in spite of this different physics, the numerical simulations lead to spectra of Langmuir waves with frequencies mainly below the pump frequency. These computed spectra thus have features in common with the 430 MHz radar backscatter spectra observed during ionospheric heating [*DuBois et al.*, 1988]; the theory also explains the observed height of the enhanced plasma line [*Muldrew and Showen*, 1977; *Birkmayer et al*, 1986] in a very natural manner.

There are, however, some difficulties with this alternative interpretation of at least some features of the observed spectra. If the Langmuir cavitons have life times of much less than a millisecond, then it is very difficult to explain the observed bandwidths of the OTSI line which can be as low as 15 Hz as shown by Figure 13. It is even more difficult to explain the results of *Sulzer et al.* [1984] who found that in 430-MHz radar backscatter observations during HF transmissions with two frequencies 1 to 10 kHz apart that the narrow OTSI line was replaced by an equally narrow line whose Doppler shift is equal to the arithmetic mean value of the two pump frequencies. Such a result is consistent with the linear theory of *Fejer et al.* [1978]; it is not consistent with a process of direct conversion as described by *Wong et al.* [1981].

Some aspects of the 430-MHz radar backscatter spectra are therefore difficult to explain in terms of the SLT model of *Russell et al.* [1986, 1988] and *DuBois et al.*, [1988]. In view of these difficulties of explaining all aspects of the 430 MHz radar backscatter spectra observed at Arecibo in terms of SLT, the possibility of alternative mechanisms should not be ignored. For this reason the different interpretations of similar observational results by *Muldrew and Showen* [1977] and by *Isham et al.* [1987], mentioned earlier, will now be considered in more detail.

The interpretation of *Isham et al.* [1987] was in terms of localized density depletions which grow from the noise in less than 10 ms after switching on the HF transmissions and have linear dimensions smaller than 10 m. They justified that interpretation by their observation that the depletions were already present in less than 10 ms. They were not able to observe the initial growth of the depletions and therefore could not exclude the possibility that the ducts, used in the interpretation of *Muldrew and Showen* [1977], were already present before the HF transmissions were switched on, having been produced during earlier on periods of HF transmissions.

This is precisely the assertion made by *Muldrew* [1988] in a paper in which references are given to earlier papers by him, defending and further developing the original interpretation by *Muldrew and Showen* [1977] in terms of ducts. *Muldrew* [1988a] suggests that the localized plasma density depletions observed by *Isham et al.* [1987] have not grown from the thermal level during the first 5-10 ms after the HF transmissions were switched on. He suggests instead that the depletions are field-aligned ducts that did not have enough time to decay by more than a factor of 2 during the 45-s off period. Moreover, he supports this suggestion by the results of his numerical computations. In those computations he takes into account the effects of both the ponderomotive force and the heating due to parametrically excited Langmuir waves. He proposes therefore that the parametric growth within the preexisting ducts of propagating trapped Langmuir waves detectable by the Arecibo radar occurs within a few milli-seconds after transmitter turn-on. He also suggests that the ducts, within which the plasma density is a few percent below the ambient value, have diameters of the order of 25 m or more and that they are spaced by distances of the order of 1 km. He suggests that these ducts are maintained by the effects of the ponderomotive force and of heating due to parametrically excited trapped Langmuir waves which are present during the on periods. Moreover, he explains the overshoot in terms of increasing collisionless damping of the propagating trapped Langmuir modes (not at the point where they are detected by the radar but closer to the center of the duct where the plasma density is lower) as the duct deepens. The deepening is caused, according to him, initially by the effect of the ponderomotive force but after the first 50-100 ms almost entirely by an increase in electron temperature. This decrease in electron density due to the increased electron temperature

is caused by upward and downward diffusion of the plasma along the field lines, a process that has some built-in inertia.

*Muldrew* [1988] suggests that these strong isolated ducts should not be confused with the weaker field-aligned irregularities responsible for HF, VHF, and UHF radar backscatter. He suggests that the strong isolated ducts were not detected by their effect on the chirp spectrum of the natural plasma line, observed during the 45-s off period by *Isham et al.* [1987], on account of their isolated nature.

*D.B. Muldrew* (private communication, 1988) makes the further suggestion that some of the observations of our present paper probably could also be explained by the isolated ducts as will be discussed shortly.

Neither *Muldrew's* [1988] latest published work nor his earlier work cited in it contains a detailed theory or a full numerical simulation of the original development of his strong isolated ducts out of the thermal level or out of another low level of pre-existing density perturbations (possibly weak natural ducts), following a sufficiently long period without heating. A more complete theory would also have to explain why the spectrum of propagating trapped Langmuir waves is not subject to collapse as predicted by SLT theory. Until such further developments *Muldrew's* [1988] work must be regarded as tentative but deserves consideration for the reasons mentioned earlier.

The possibility of experimental tests of the existence of strong isolated ducts should be considered, possibly by suitable rocket or satellite observations. It should be mentioned in this connection that in Figure 4 of *Farley et al.* [1983], representing the percentage density deviations (after detrending) measured along the path of a satellite through the heated region with a resolution of 70 m in distance, shows two narrow negative peaks of over 2% about 8 km apart. These measurements could be interpreted in terms of isolated field aligned density depletions (ducts). If the two negative peaks were caused by ducts of 25 m or only slightly larger diameter, below the 70 m resolution of the measurements, then the actual density depletion could have exceeded 5%. In view of the one-dimensional nature of the measurement, the ducts must have been considerably closer to each other in two dimensions than 8 km; 0.5 km would be a better estimate from Figure 4 of *Farley et al.* [1983] for a duct diameter of 25 m.

The following discussion considers the possibility of providing at least tentative explanations of some of our present observations not explained at present by strong Langmuir turbulence theory in terms of the strong isolated ducts of *Muldrew* [1988a].

The fast temporal variations of the power in the enhanced plasma line, described in Section 2, could be tentatively explained (D.B. Muldrew, private communications, 1988) by the effect of the ponderomotive force of parametrically excited Langmuir waves, trapped in isolated field aligned density depletions (ducts). After transmitter turn-on and the resulting rapid parametric growth of Langmuir waves, the ponderomotive force has the effect of reducing the density in a preexisting duct. After a time of the order of 5-10 ms of this continued density decrease, collisionless damping extinguishes first the Langmuir waves responsible for the observed radar backscatter and eventually all the Langmuir waves. The density in the ducts then first continues to decrease on account of ion inertia but eventually increases until Langmuir waves can grow again and the process is repeated. While this repetitive process is going on, the electron temperature in the duct increases and the density decreases slowly until eventually parametric excitation ceases altogether in some of the ducts and sometimes in all the ducts by the overshoot process of *Muldrew* [1988]. The almost periodic pulsations of Figure 1 between 1400 ms and 1700 ms could have resulted from the presence of Langmuir waves capable of being detected by the radar in only a single duct. The finite bandwidth which characterizes all the 430-MHz OTSI lines observed with a frequency resolution of the order of 1 Hz, could be interpreted as being the result of such periodic pulsations even when three or more ducts contribute to the observed enhanced plasma line whose power then does not show pulsations.

The results shown by Figures 6 and 7 of Section 3 could be explained [*D.B. Muldrew* private communications, 1988] by the expected effect of changing the duty cycle on the overshoot mechanism of *Muldrew* [1988] mentioned earlier. With the shorter duty cycle in Figure 6, the longer off periods gave more time for the electron gas to cool until eventually the increased electron temperature and the resulting density depletion reached during the on period did not produce enough collisionless damping to cause a drop in the power backscattered by Langmuir waves and thus an observable overshoot.

It was mentioned earlier that other effects [*Graham and Fejer*, 1976] related to the thermal parametric instability [*Vaskov and Gurevich*, 1975; *Grach et al.*, 1977; *Das and Fejer*, 1979; *Inhester*, 1982] can contribute to the overshoot. However, as pointed out by *Djuth and Gonzales* [1986], at Arecibo for a heating frequency near 5.1 MHz pump depletion is usually insufficient to explain the overshoot by these other effects. Under such circumstances the overshoot mechanism of *Muldrew* [1988] is the only existing explanation at present.

Summing up, the main purpose of this paper was the description of the results of recent observations of the enhanced plasma line at Arecibo. Some of these result can be explained [*DuBois et al.*,1988] in terms of the well established theories and simulations of strong Langmuir turbulence. However, other results such as the observed variations in the enhanced plasma line power on the time scale of tens of milliseconds and the observed very narrow spectral feature with a Doppler shift equal to the pump frequency (or to the arithmetic mean value of two pump frequencies) cannot at present be interpreted in terms of strong Langmuir turbulence. Very tentative explanations of those features in terms of ducts [*D.B. Muldrew*, 1988; *D.B. Muldrew*, private communication, 1988] were suggested but further work is needed either to put those explanations on a more firm theoretical basis or to seek alternative explanations, possibly by further developments of SLT theory.

## APPENDIX

The randomly coded long pulse is generated by phase coding with a baud length $t_b$ in such a manner that at the end of each baud there is a probability of 0.5 for a phase reversal.

Assume for the moment that the scatter comes from a single height at a single frequency. Assume further that the decoding has a phasing error $t_e$, defined as the time difference between the decoding sequence used in the receiver and the coding sequence of the scattered signal received from the

ionosphere. In the experiments several decoding sequences, with starting times spaced $t_b$ apart, were used. For two of these decoding sequences $|t_e| < t_b$ was satisfied, except in the special case when $t_e=0$ was satisfied for one of the decoding sequences.

The amplitude of the detected echo is reduced if there is a coding error because at every phase reversal there is a time of length $t_e < t_b$ during which the phase of the decoded signal is reversed. Since the probability of a phase change after a given baud is 0.5, these contributions with the wrong phase to the Fourier component occur $t_e < 2t_b$ fraction of the time during the coded long radar pulse of much greater length than $t_b$ contributions with the correct phase therefore occur $|1 - t_e|/2t_b$ fraction of the time. The fractional reduction in the amplitude of the Fourier component caused by the decoding error is therefore $(1-|t_e|/2t_b) - t_e/2t_b = 1 - t_e/t_b$. This expression vanishes for $t_e = t_b$ as it should. With the notation $|t_e|/t_b = p$ the fractional reduction in the power of the Fourier component becomes $(1\text{-}p)^2$.

As was mentioned in the body of the paper, several spectra for different time delays of the decoding sequence were obtained every 5s; the spectrum with the largest peak power density was accumulated in the second highest of the range bins established in the analysis program. It seems therefore reasonable to assume that the values of $t_e/t_b$ in the second highest range bin were distributed evenly between -0.5 and 0.5 because the time delay of the backscatter varied by much more than $t_b$ during the accumulation process. Therefore p was distributed evenly between 0 and 0.5. As was explained in the body of the paper, spectra during whose accumulation process the time delay of the received scatter varied by less than $t_b$ during a substantial fraction of the time, were rejected.

For the highest range bin, $t_e/t_b$ will be evenly distributed between -1.5 and -0.5. For values of p larger than 1 only clutter is obtained after averaging over a large number of randomly selected codes, and therefore $p$ will be evenly distributed between 0.5 and 1. For the third highest range bin $t_e/t_b$ will be evenly distributed between 0.5 and 1.5 and therefore p will be evenly distributed between 0.5 and 1. The power ratio $r$ of the power in the second highest range bin to the power in one of the neighboring range bins is therefore expected to be

$$r = \frac{2\int_o^{.5}(1-p)^2dp}{\int_{.5}^{1}(1-p)^2dp} = 14 \qquad (1)$$

The factor of 2 in the denominator is needed because $t_e/t_b$ varies between -0.5 and 0.5, but the corresponding value of p only varies between 0 and 0.5.

The assumption used in the derivation of equation 1 about the even distribution of $t_e/t_b$ in the mentioned intervals is likely to be violated if during a large part of the time over which the spectra were averaged, the height from which the scatter was received remained nearly constant; such spectra were disregarded as was mentioned in the body of the paper.

The earlier assumption of a single frequency was in no way restrictive; in view of the linear nature of the process the same arguments can be applied to any Fourier component.

As mentioned in the body of the paper, the observed values of r were much less that the value of 14 predicted by equation 1 for scatter from a single height. The observed values of $r$ should therefore lead to some estimate of the range of heights from which scatter was received. For this purpose the assumption will be made that the scatter is distributed uniformly over a range of heights, well knowing that the assumption will not be satisfied in practice but having no a priori knowledge about the nature of the height distribution of the scattered power.

Consider scattering from a height for which the time delay of the scattered echo differs by $q$ fractional bauds from the time delay corresponding to the center of the height range over which a uniform distribution of the scatter is assumed. For $q = 0$ the values of $t_e/t_b$ will then evenly distributed, for the second highest range bin, between -0.5 and 0.5 as before, However, for a non zero value of q the distribution will be even between -0.5+q and 0.5+q and therefore the numerator in equation 1 will be replaced by

$$\int_o^{.5-q}(1-p)^2dp + \int_o^{.5+q}(1-p)^2dp = 7/12 - q^2 \qquad (2)$$

and the denominator in (equation 1) will be replaced by

$$\int_{.5+q}^{1}(1-p)^2dp = 1/24 - q/4 + q^{2/2} - q^{3/3} \qquad (3)$$

by similar arguments.

Integration of the expressions equation 2 and equation 3 from $q = -Q$ to $q = Q$ then results in the equation

$$r = (14 - 8Q^3)/(1 + 4Q^3) \qquad (4)$$

where $2Qt_b$ is the spread in the time delays of the received scatter. For $Q = 0$ equation 4 yields the correct value of $r$=14. For an observed value of $r$=10, equation 4 yields $Q = 0.44$. For the baud length used in the experiment described in the body of the paper this value of $Q$ implies a spread over a height range of ±0.53 km with the assumption of uniform spread over that range.

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ATTACHMENT 3

# Simultaneous observations of 46.8 MHz and 430 MHz radar backscatter from HF-induced ionospheric Langmuir turbulence

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ABSTRACT

Simultaneous high resolution spectra of the upshifted enhanced plasma line were obtained with the 46.8 MHz and 430 MHz Arecibo radars in the presence of HF transmissions at two closely spaced frequencies. The spectra obtained with the 46.8 MHz radar showed two narrow features with positive Doppler shifts equal to the two closely spaced frequencies of the HF transmissions; all the spectral power was contained in those two narrow features. The spectra obtained with the 430 MHz radar showed a single narrow feature with a positive Doppler shift equal to the arithmetic mean of the same two closely spaced frequencies; the spectral power in that narrow feature contained about 3% of the total spectral power. The present results broadly confirm the tentative interpretation of earlier observations with a 46.8 MHz radar at Arecibo. The results also show the fundamental difference in the physical processes leading to the enhanced plasma line spectra observed with the two radars.

INTRODUCTION

In 1981 a 46.8 MHz radar was temporarily installed at Arecibo by the Max-Planck-Institut fur Aeronomie for observations of backscatter from the middle atmosphere. That opportunity was used to carry out a few observations of the upshifted enhanced plasma line with the 46.8 MHz radar. Before 1981 only the 430 MHz radar has been used for exploring the properties of the enhanced plasma line.

It was concluded from those observations (Fejer et al., 1983) that the spectrum of the 46.8 MHz enhanced plasma line showed no sign of the excitation of the parametric decay instability (PDI). Backscatter was observed over a narrow frequency band of about 5 Hz width with a positive Doppler shift which, apart from a small correction for plasma drift velocity, was equal to the frequency of the HF transmissions.

Two possible mechanisms were put forward to explain the observations (Fejer et al., 1983). The first was scattering of the pump wave by HF-induced slowly varying irregularities in the plasma density into Langmuir waves by essentially the same mechanism that Dawson and Oberman (1962,1963) used in their calculation of rf conductivity of a plasma; their slowly varying irregularities were the ion acoustic waves existing in a plasma in thermal equilibrium.

The second mechanism was in terms of the oscillating two-stream instability (OTSI), a parametric instability derived from the

same linear dispersion relation (Nishikawa, 1968a,b; Kaw and Dawson, 1969) as the parametric decay instability (PDI). The first mechanism appeared more plausible because it was difficult to explain why the OTSI (invoked by the second mechanism) should be observed regularly with the 46.8 MHz radar without ever observing any sign of the PDI.

No decisive choice between those two mechanisms could be made on the basis of the 1981 observations. The main purpose of the present observations was to provide conclusive evidence on the basis of which such a decisive choice could be made. For this purpose simultaneous observations of enhanced plasma line spectra (backscatter spectra from HF-induced Langmuir turbulence) were to be obtained with the 430 MHz and the 46.8 MHz radars at the Arecibo Observatory. The observations were to be carried out in the presence of CW high power HF transmissions at two closely spaced frequencies from Islote, about 17 miles northeast of the observatory.

Theory (Fejer et al., 1978) predicts and past observations with the 430 MHz radar (Showen et al., 1978; Sulzer et al., 1984) show that if two closely spaced pump frequencies are used then the narrow OTSI line is essentially replaced by a single narrow spectral feature whose Doppler shift is equal to the arithmetic mean value of the two pump frequencies. Therefore if the narrow spectral feature observed with the 46.8 MHz radar in 1981 was a manifestation of the OTSI then, in the presence of HF transmissions of equal power at two closely spaced frequencies, a single narrow

spectral feature with a Doppler shift equal to the arithmetic mean of the two pump frequencies would be expected. However, if scattering of the pump wave by irregularities in the plasma density into Langmuir waves was the operating mechanism then two narrow spectral features with Doppler shifts equal to the two pump frequencies would be expected.

The observational results are described in the next section. Those results are discussed further in the light of existing theories of Langmuir turbulence in the last section.

## OBSERVATIONS

Both the 46.8 MHz radar and the 430 MHz radar were operated with a pulse length of 8 microseconds and an inter-pulse period (IPP) of 1200 microseconds. Coherent sampling of the backscattered signal was carried out every 2 microseconds, alternating between the outputs of the 46.8 MHz and the 430 MHz receivers, after conversion to the same intermediate frequency. Spectra of the upshifted enhanced plasma line were then obtained from arrays containing 256 complex sample values for the same time delay (radar range) from 256 consecutive IPP-s. For each range a large number of power spectra were accumulated before writing on tape. The approximate range of the plasma line echo was known from an oscilloscope display; the spectra for several ranges 300 m ( 2 microseconds) apart were written on tape. As mentioned earlier, the 46.8 MHz and the 430 MHz radar receiver outputs were sampled alternately. For either one of the two

radars the spectra written on tape were therefore 600 m apart in range (height).

Figure 1 shows two such spectra obtained on 31 May, 1988 at 22:59:20 AST. Four HF transmitters, operating at a single frequency of 5.1 MHz, were feeding 25 kW each into an antenna array system of approximately 23 db gain. The transmitters were operated at only a quarter of their usual power of 100 kW because it was known (Sulzer et al., 1989) that the OTSI line observed with the 430 MHZ radar is more narrow for lower powers and is often unobservable at full power.

On the spectrum obtained with the 46.8 MHz radar the frequency deviation from 51.9 MHz + 50 Hz is shown. The 50 Hz offset was introduced to avoid confusion with a small instrumental peak due to imperfection of the coherent detector; that peak is too small to be seen on the linear display of spectral power density in Figure 1 but was easily visible in other cases (not shown here) where the enhanced plasma line was weaker. No similar offset was used for the spectrum obtained with the 430 MHz radar.

For each of the two radars the spectrum for the range that resulted in the largest peak spectral power density was chosen for Figure 1. There was no systematic difference between the ranges thus chosen for the two radars; for Figure 1 the range chosen for the 46.8 MHz radar was 900 m (6 microseconds) greater than the range chosen for the 430 MHz radar.

The 430 MHz spectrum of Figure 1 shows the OTSI line with a half-power bandwidth of about 40 Hz; in the absence of ionospheric

drifts the line would be centered on 0 Hz (which corresponds to 435.1 MHz at the receiver input). About 97% of the spectral power is contained in the decay line and cascade which are aliased into the 833.3 Hz wide spectrum of Figure 1 as almost uniformly distributed noise, leaving only 3% of the power in the OTSI line.

The 46.8 MHz spectrum of Figure 1 shows a line of about 5 Hz half-power width that would be centered on -50 Hz (which corresponds to 51.9 MHz at the receiver input) in the absence of ionospheric drifts. All the spectral power is contained in that line; this confirms the results of the 1981 observations (Fejer et al., 1983).

Figure 2 shows enhanced plasma line spectra obtained a few minutes earlier with the same two radars on 31 May, 1988 at 22:56:14 AST, using two HF pump frequencies differing by 200 Hz. Two of the HF transmitters, operating at 5.1 MHz, were each feeding 25 kW into one half of the antenna array system; the other two transmitters, operating at a frequency of 5.1 MHz + 200 Hz = 5.1002 MHz, were feeding 25 kW each into the other half of the antenna array system.

The 430 MHz spectrum of Figure 2 shows the expected spectral peak at about 100 Hz, representing backscatter by Langmuir waves whose frequency is approximately equal to the arithmetic mean of the two pump frequencies.

The 46.8 MHz spectrum of Figure 2 shows two spectral peaks near 50 Hz and 150 Hz, representing backscatter by Langmuir

waves whose frequencies are approximately equal to the two pump frequencies.

The 46.8 MHz spectrum of Figure 2 shows no sign of backscatter by Langmuir waves whose frequency is near the arithmetic mean of the two pump frequencies. This is the principal result of the present observations. It fully confirms the tentative suggestion by Fejer et al. (1983) that the 46.8 MHz plasma line has no relation to the OTSI (the second mechanism mentioned in the Introduction). The results of the present observations have therefore made a decisive choice between the two mechanisms mentioned in the Introduction possible. The 46.8 MHz plasma line must be related to very slowly varying irregularities in the plasma density on which the pump wave is somehow converted to Langmuir oscillations or waves that can backscatter the radar waves (the first mechanism mentioned in the Introduction). The question of the precise nature of this conversion process is discussed in the next and concluding section.

## DISCUSSION

The present observations throw little light on the nature of the irregularities in the plasma density that are indirectly responsible for the 46.8 MHz plasma line by scattering the HF pump wave into Langmuir waves.

Fejer et al. (1983) suggested that the HF pump wave is scattered by weak small-scale field-aligned irregularities in the plasma density into Langmuir waves. Such Langmuir waves

would have wave vectors that are initially perpendicular to the magnetic field and therefore can not satisy the Bragg backscattering condition for the 46.8 MHz radar. A way out of this difficulty was suggested by Fejer et al. (1983) in terms of the density stratification resulting from the Airy structure of the pump wave through the action of the ponderomotive force and heating. The Bragg backscatter condition could then be satisfied through subsequent propagation and refraction of the scattered Langmuir waves in the density stratification. However unrealistically high values of the HF pump field, invoking enhancement by self-focusing, had to be assumed by Fejer et al. (1983) for this purpose. Their assumed pump fields would be even less realistic for the present observations where the pump power was only a quarter of its customary value.

It should be mentioned here parenthetically that attempts, based on a technique suggested by Fejer (1983), were made to detect the Airy density stratification in the vicinity of the height of reflection by one of the present authors (J. A. F) in collaboration with Dr. C. A. Gonzales in 1983 at Arecibo; the negative results of those attempts were not published. The Airy density stratification well below the height of reflection has been detected both in the USSR (Belikovich et al., 1975, 1977, 1978) and at Arecibo (Fejer et al., 1984) by a different technique.

In addition to overestimating the inhomogeneity of the ionospheric plasma due to the Airy pattern of the HF pump field

Fejer et al. (1983) probably underestimated the strength of short scale field-aligned irregularities. It seems almost certain (Muldrew, 1988; Sulzer et al., 1989; Fejer et al., 1990) that isolated field-aligned depletions of the plasma density by several percent (ducts) exist during CW HF transmissions. It is also known (Muldrew and Showen, 1977; Birkmayer et al., 1986; Djuth at al., 1990, Sulzer et al., 1990) that the enhanced plasma line observed with the 430 MHz radar is not generated at the height where Langmuir waves satisfy their dispersion relation in the unperturbed medium but rather at a range of heights extending upward to the reflection height.

The presence of ducts was first invoked by Muldrew (1978) to explain the observations of Muldrew and Showen (1977) which showed that the enhanced plasma line is generated above the height where Langmuir waves satisfy their dispersion relation in the unperturbed ionosphere. An alternative explanation in terms strong Langmuir turbulence was suggested by DuBois et al. (1988, 1990).

The explanation in terms of ducts raises the question of applicability of the simple linear uniform medium theory (Fejer et al., 1978) that predicts a narrow spectral feature with a Doppler shift equal to the arithmetic mean of the two pump frequencies. A modification of that theory in terms of modes within a duct along the lines of the work of Rypdal et al. (1979) should be possible.

There is at present no quantitative theory that explains

the observed spectral feature at the arithmetic mean of the two pump frequencies in terms of strong Langmuir turbulence (DuBois et al., 1990) although a qualitative explanation in terms of caviton correlations has been given by those authors.

Returning to the question of the upshifted plasma line observed with the 46.8 MHz radar, our knowledge of the precise nature of the plasma irregularities is insufficient for the formulation of a precise theory at present. The process could resemble the type of resonant excitation discussed for example by DuBois et al. (1990) in a different context but it would occur in larger static depletions in plasma density rather than the very small quasi-periodically collapsing cavitons considered by those authors. Alternatively the process could be a combination of scattering on density irregularities and subsequent propagation but the details of that process would differ considerably from that outlined by Fejer et al. (1983).

In addition to the observations of 31 May 1988, described here, other more extensive observations of the 46.8 MHz plasma line have been carried out by Djuth and Sulzer (private communication), using a single pump frequency, during the same campaign at the Arecibo Observatory in 1988. The results of those observations and their interpretation will be published separately.

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CAPTIONS FOR FIGURES

Figure 1. Spectra of the upshifted enhanced plasma line obtained with the 46.8 MHz (A) and the 430 MHz (B) radars during HF transmissions at a frequency of 5.1 MHz. Radar pulses of 8 microsecond length were transmitted every 1.2 ms by both radars; the spectra are therefore 833.3 Hz wide. Zero on the frequency scales corresponds to 51.90005 MHz (A) and 435.1 MHz (B) respectively.

Figure 2. Spectra of the upshifted enhanced plasma line obtained with the 46.8 MHz (A) and the 430 MHz (B) radars during simultaneous HF transmissions of equal power at the two frequencies of 5.1 MHz and 5.0002 MHz. Radar pulses of 8 microsecond length were transmitted every 1.2 ms simultaneously by both radars; the spectra are therefore 833.3 Hz wide. Zero on the frequency scales corresponds to 51.90005 MHz (A) and 435.1 MHz (B) respectively.

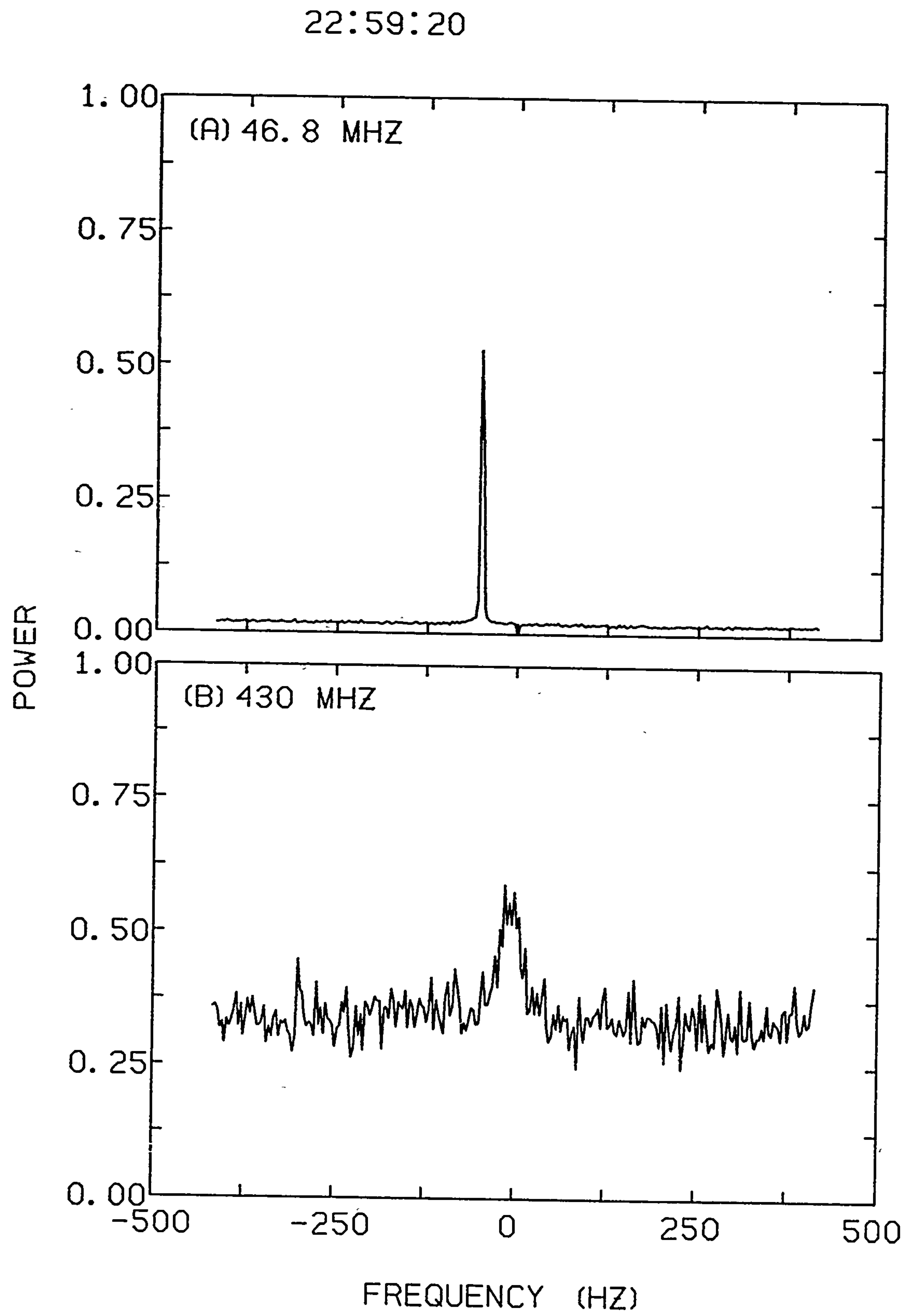


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**FIGURE 1**

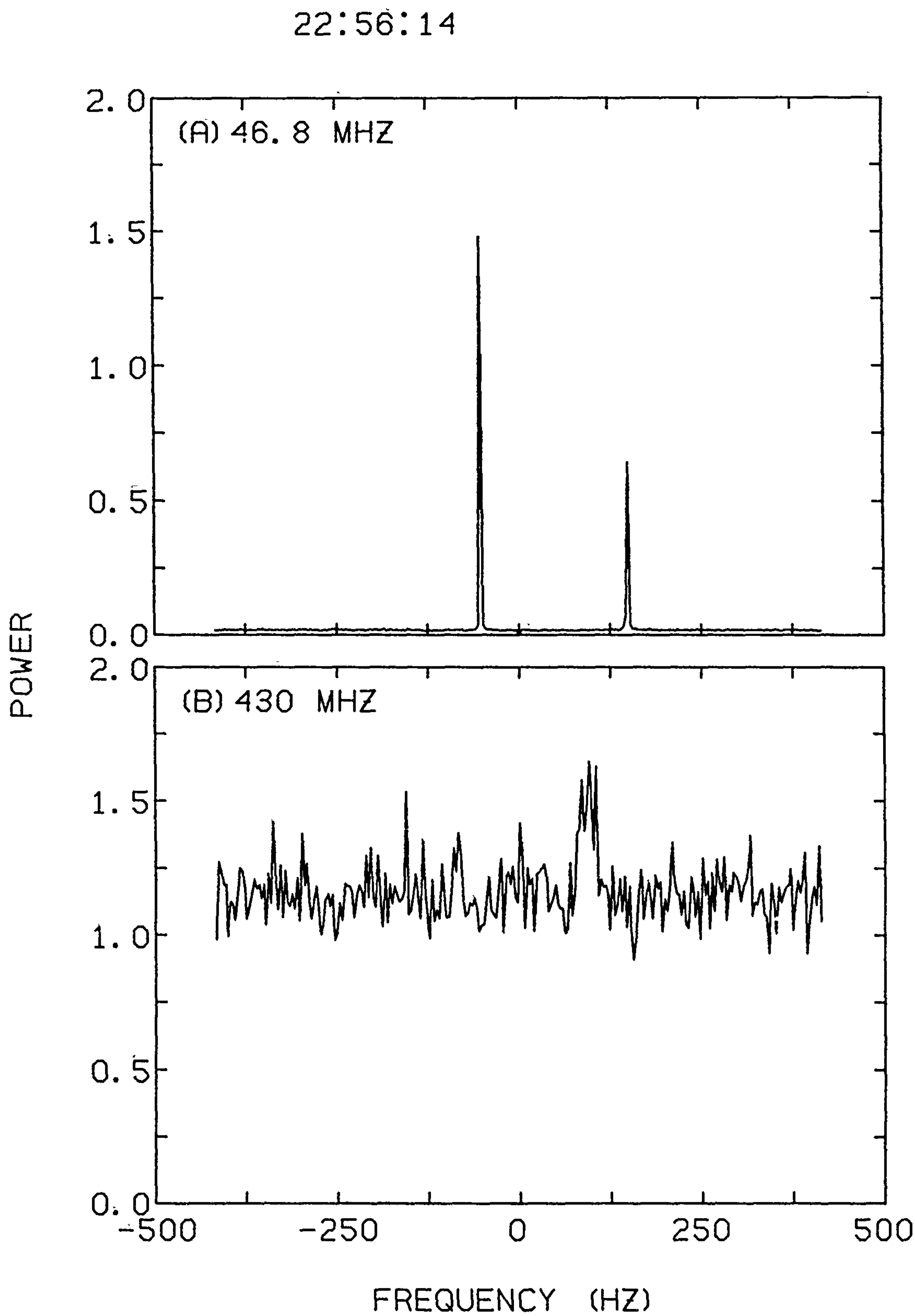


**FIGURE 2**

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ATTACHMENT 4

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# PHYSICAL PROCESSES OF IONOSPHERIC HEATING EXPERIMENTS

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## ABSTRACT

Plasma instabilities, resulting from the presence of a powerful radio wave in ionospheric heating experiments, are reviewed. First the linear theories of the parametric decay instability and of the oscillating two-stream instability are considered. The saturation theories of these instabilities for weak pump waves are then outlined and their results are shown to be in reasonably good agreement with observations.

Different theories are needed for excitation by strong pump waves. Such theories generally invoke the formation of cavitons. Observations suggesting the formation of cavitons are outlined. The differences between caviton properties derived from observations and the properties derived from existing theories are pointed out.

The effect of plasma instabilities on the creation or modification of a population of energetic electrons in ionospheric heating experiments is demonstrated by indirect observations of the temporal evolution of energetic electron fluxes after the heating transmitter is switched on.


## 1. INTRODUCTION

Ionospheric heating experiments are conducted using facilities capable of radiating electromagnetic waves of very high power towards the ionosphere. The waves are usually radiated directionally at vertical incidence at frequencies somewhat below the critical frequency and are therefore reflected. There is thus no clear distinction between ionospheric heating facilities and very powerful short wave transmitters built for communication, apart from the purpose for which they have been built and apart from the need of elaborate diagnostic equipment in heating facilities.

It was customary to assume that the response of the ionosphere to a wave incident on it was linear until the modulation of a powerful long wave radio station was heard on the carrier of another station /1/. The effect was attributed to the modulation of the electron temperature in the D- and lower E-region by the waves from the powerful station /2/.

Another form of nonlinearity results from the ponderomotive force /3/ which is the equivalent for a plasma of the radiation pressure force in vacuum.

In principle the nonlinear effects of heating and of the ponderomotive force (the nonlinearity results from the dependence of both effects on the square of the electric field) are present for any strength of an incident radio wave. In practice the effects only become detectable for a relatively powerful wave. The nonlinear effects of heating have been used both, for the investigation of the ionosphere /4/ and for the generation of ELF/VLF waves /5/.

If the incident power density is increased sufficiently then the ionosphere becomes unstable to the effects of heating nonlinearities and/or to the effects of ponderomotive nonlinearities. The result is the spontaneous growth of perturbations (waves) in the ionospheric plasma. Such instabilities were first observed at Platteville, Colorado where the first of a new generation of ionospheric heating facilities started operation /6/. Some earlier observations near Moscow, USSR were later reinterpreted /7/ in terms of such instabilities.

Several other ionospheric heating facilities started operation since 1970, at Arecibo, Puerto Rico, near Tromsø Norway, and in the Soviet Union near Gorky, near Moscow and near Murmansk.

This review will be restricted to the discussion of plasma instabilities excited in ionospheric heating experiments. Some nonlinear effects not directly related to instabilities are reviewed in /5/. The book of Gurevich /8/ is a particularly useful source of information on this as well as other aspects of ionospheric heating experiments.

It is usual to call the instabilities excited in ionospheric heating experiments parametric instabilities if the nonlinearity involved is ponderomotive. The term thermal parametric instability will be used here if the nonlinearity is dominated by heating rather than the ponderomotive force. It is customary to refer to the incident powerful radio wave that causes the growth of other waves, as the pump wave.

The linear theory of two parametric instabilities, the parametric decay instability or PDI and the oscillating two-stream instability or OTSI, will be reviewed in Section 2. The saturation of the PDI for weak pump waves will be considered in Section 3 where results of the observations will be compared with theoretical results. Thermal parametric instabilities such as self-focusing and the generation of short scale field-aligned irregularities will be reviewed very briefly in Section 4. The saturation problem for strong pump waves and the formation of cavitons will be considered in Section 5. In Section 6 indirect observations of the acceleration of electrons from the tail of the Maxwellian distribution at night and of the modification of the photoelectron fluxes in daytime, during ionospheric heating experiments, will be described. A few concluding remarks are made in Section 7.

## 2. THE PDI AND THE OTSI

The PDI and the OTSI both play an important role in ionospheric heating experiments. Their theory and references to earlier work are given for example by /9/.

In the PDI the incident electromagnetic wave of high frequency, the pump, decays into a Langmuir wave of slightly lower high frequency and an ion acoustic wave of low frequency. The Langmuir wave results from the scattering of the pump wave by the ion acoustic wave. The ion acoustic wave, in turn, results from the ponderomotive nonlinearity which produces a force at the difference frequency of the two high frequency waves. For a large enough pump field the feedback resulting from those two processes leads to instability.

In the OTSI a spatially periodic but temporally aperiodic plasma density perturbation scatters the electromagnetic pump wave into a standing Langmuir wave. The ponderomotive force due the interference pattern of the pump wave with the standing Langmuir wave generates the temporally aperiodic density perturbation and thus completes the feedback loop. Such parametric instabilities in which temporally aperiodic density perturbations scatter the pump wave and thus spatially modulate the pump field, are usually called modulational instabilities.

The linear growth rates of these two instabilities for typical ionospheric conditions near the first Airy maximum of the pump field are shown by Figure 1 as a function of the pump electric field. The parameters used are essentially the same as those used in /10/ but the dispersion relation used here is based on kinetic theory rather than fluid theory. The dispersion relation and the values of the parameters used in the computations leading to Figure 1 are given in the Appendix.

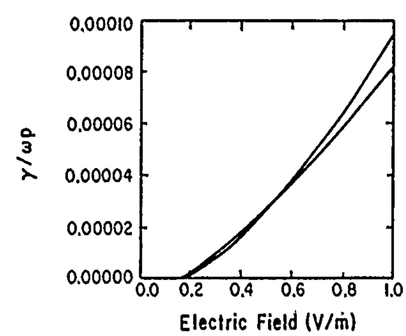


Fig. 1. Growth rates of the OTSI and of the PDI as functions of the pump electric field strength $E_0$ for $\omega_0/\omega_p = 1.0017$

Note that the two curves of Figure 1 intersect for a field strength of about 0.6 V/m, about 11 db above threshold. The strength of the pump field at the first Airy maximum, 170 m below the theoretical reflection height of the pump wave of ordinary polarization, will certainly exceed 0.6 V/m for the full power of the Arecibo heating facility. Therefore at full power the growth rate of the OTSI will be greater than the growth rate of the PDI. However for weaker powers, still well above the threshold of the instabilities, the growth rate of the PDI will be the greater one.

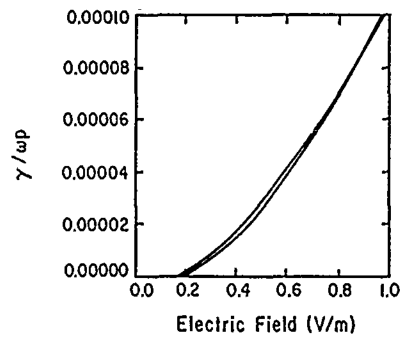


Fig. 2. Growth rates of the OTSI and of the PDI as functions of the pump electric field strength $E_0$ for $\omega_0/\omega_p = 1.0084$

Figure 2 represents conditions 840 m below the reflection height where in the example treated in /10/ the dispersion relation of the Langmuir waves, detected by the 430 MHz radar at Arecibo by backscatter, is satisfied in the unperturbed ionosphere. At that height the pump field is weaker and according to Figure 2 the curves intersect for a larger pump field of 0.9 V/m which may not be exceeded even at full power. It should be stressed that these crude estimates neglect the effects of the geomagnetic field.

The linear growth rate determines only the initial growth of the excited waves. This growth must be limited by some form of saturation mechanism. Such mechanisms will be considered in the following sections.

## 3. SATURATION OF PARAMETRIC INSTABILITIES FOR WEAK PUMP WAVES

Saturation of parametric instabilities by successive parametric decay was numerically simulated for moderate pump powers, less than 4 times above threshold /11,12,13/, extending the one dimensional treatments in /14/ and in /15/, both based on the original suggestions in /16/.

The simulations assumed a uniform oscillating pump field in a uniform medium. They had the purpose of explaining the initial observations of backscatter spectra from parametrically excited Langmuir waves /17,18/ with the 430 MHz radar at Arecibo. Such spectra will be called here spectra of the enhanced plasma line. In contrast, spectra of incoherent backscatter from Langmuir waves will be called here spectra of the natural plasma line, irrespective of whether the spectra are enhanced by energetic electrons or not.

The results of the simulations /11,12,13/ suggest that the parametrically excited unstable waves form angles of less than 25° with the uniform pump electric field which at Arecibo, for the ordinary wave and for the heights where the Langmuir waves detected by the 430 MHz radar satisfy the dispersion relation, is very nearly linearly polarized along the geomagnetic field. This is not the case for the UHF radar at Tromsø; numerical simulations for the more complicated polarization of the pump electric field for Tromsø do exist /19/ but will not be discussed here.

In the heating experiments at Arecibo the radar beam typically makes an angle of about 45° with the geomagnetic field and therefore unstable Langmuir waves predicted by the numerical simulations should not be detected at all by the 430 MHz radar at Arecibo. That radar should instead detect the Langmuir waves resulting from the scattering of the unstable Langmuir waves and of the pump wave by the thermal ion acoustic waves. The latter are familiar from the theory of the double-humped spectrum of incoherent backscatter. The resulting much weaker Langmuir wave spectra are shown for example by Figure 6 (in which the lowest curve was labelled erroneously 5 instead of 0.5) of /12/. Note that there is no sharp separation between spectra below and above threshold. The predicted much stronger spectra of the unstable waves that should not be observable according to the above theories by the 430 MHz Arecibo radar, are shown, for example, by Figures 1, 2 and 3 of /11/.

An apparent theoretical limit to successive parametric decay producing a cascade of Langmuir waves should be pointed out here. The limit is suggested by the one-dimensional graphical construction shown by Figure 1 of /20/. That construction leads to a finite limit to the number of members of the cascade. Since the simulations lead to a rapidly increasing number of members of the cascade with increasing pump power, the cascade is only possible for relatively

low pump powers. Indeed below a critical value of the ratio of the pump frequency to the plasma frequency cascading becomes impossible; this is, however, of no practical importance because the linear thresholds of the PDI and OTSI are not exceeded under these conditions.

Turning to the observations, Figure 9 of /21/, obtained at night in the absence of photoelectrons, shows enhanced plasma line spectra of various strengths for different pump powers. It shows a double humped very weak spectrum below threshold and a few weak spectra which exceed the system noise (mainly receiver noise and galactic noise) by 10 - 16 db. These spectra are not unlike those of Figure 6 in /12/ for below and somewhat above threshold.

Figure 9 of /21/ also shows, however, very much stronger spectra. Those are the enhanced plasma line spectra seen more commonly. The weaker spectra would, in fact, be difficult to observe in daytime when the natural plasma line, enhanced by photoelectrons, exceeds the system noise by factors much larger than 10.

The strong spectra in Figure 9 of /21/ are quite unlike those of Figure 6 in /12/; they resemble spectra in Figures 1, 2 and 3 of /11/ more closely.

A simple explanation for these strong spectra was suggested by Muldrew /22/. He suggested that the Langmuir waves were originally generated with wave vectors forming small angles with the geomagnetic field but the waves have propagated away from the region of generation in a field aligned density irregularity, thus changing their wave vector to one allowing radar detection. The difficulty with such an explanation is the fact that the strong spectra appear within times of the order of 10 ms or less. As will be seen in the next section, this is too short a time for the formation of field-aligned irregularities.

Such irregularities are, however, known to form in ionospheric heating experiments. They are important in their own right and have important effects on the excitation of parametric instabilities. They are reviewed briefly in the next section.

## 4. THERMAL SELF-FOCUSING AND SHORT-SCALE FIELD-ALIGNED IRREGULARITIES

Thermal self-focusing was the first phenomenon noticed in the Platteville experiments by its effect on ionograms, the so called artificial spread-F /23/. Thermal self-focusing was later studied by observing the scintillation of radio waves from satellite transmitters /24/ and from extra-terrestrial radio sources /25/. Basu et al. /25/ have shown that irregularities are generated by both O and X mode heating. More recently self-focusing was studied by using its effect on the strength of the enhanced plasma line /26/ and also in situ from a satellite /27/.

Essentially thermal self-focusing can be regarded as a thermal parametric instability of the modulational type in which predominantly field-aligned irregularities with density deviations of the order of a percent develop within seconds. Their scale lengths across the geomagnetic field tend to be somewhat less than a kilometer.

The linear theory of the instability was developed in /28,29,30/. In contrast to the other parametric instabilities it can be excited by pump waves of either of the two magneto-ionic modes. The instability can also be excited by a pump wave that is not reflected by the ionosphere as the theoretical studies in /31,32/ and the observations by Basu and Basu (private communication) show.

Short scale field-aligned irregularities were studied intensely by radar backscatter in the Platteville experiment. The results were reported in the November 1974 issue of Radio Science in several papers. The scale lengths across the magnetic field were of the order of 0.3 - 3 m and the growth times were of the order of a second. Short-scale field aligned irregularities are produced by a thermal parametric instability of the modulational type in which, however, the irregularities scatter the pump wave into Langmuir waves, rather than into electromagnetic waves as in the case of thermal self-focusing. The theory of these instabilities was developed in /33,34,35,36,37,38,39/.

## 5. SATURATION OF PARAMETRIC INSTABILITIES FOR STRONG PUMP WAVES

Near the end of Section 3 the difficulties of understanding the strong spectra shown, for example, in Figure 9 of /21/ have been pointed out. Considerable progress has been made in recent years towards the understanding of those spectra, both in the theory and in the observations.

Petviashvili /40/ predicted the formation of solitons in ionospheric heating experiments. Numerical simulations based on the Zakharov equations /10,41/ confirm the formation of localized density depletions filled with Langmuir waves whose ponderomotive force causes the depletions in density by pushing out the plasma. Such depletions in density have been called cavitons, among others, by Gurevich et al. /42/ who defined them as density wells filled with Langmuir oscillations; their nomenclature will be used here.

There is increasing observational evidence that cavitons are formed in ionospheric heating experiments. The strongest evidence is that of Birkmayer et al. /43/. They used a novel technique /44/ of chirping the 430 MHz radar pulses at Arecibo. The temporal rate of change of a chirped pulse of 100 microseconds length was chosen by them to match the height gradient of the ionospheric plasma frequency near the reflection height of the pump wave. Thus in the dechirped spectrum the natural plasma line occupied a very narrow range of frequencies (apart from the effect of the

pulse length a single frequency on the assumption that over the height range of 15 km, determined bv the pulse length, the plasma frequency varies linearly with the height). The pump was cycled 15 s on 45 s off. During the off period only the natural plasma line at nearly a single frequency was seen in the dechirped spectrum. During the on period the frequency and intensity of the natural plasma line remained almost unchanged but surprisingly the enhanced plasma line appeared at frequencies lower by 100-200 kHz than the natural plasma line. This result can only be explained by assuming that for strong pump waves the enhanced plasma line is excited in local density depletions well above the height where the Langmuir waves detected by the radar satisfy the dispersion relation in the unperturbed plasma. Their results confirm earlier results of Muldrew and Showen /45/, obtained by an entirely different technique and interpreted differently at the time. The depletions appear within 10 ms (Hagfors, private communication based on later observations; Birkmayer et al. /43/ could only show that the depletions appeared within a second). It is interesting that Duncan and Sheerin /46/ observed by yet another technique that the altitude of maximum backscatter of the enhanced plasma line increases by 800-1000 m during the first 10 ms after the pump wave is switched on.

A plausible interpretation of all these observations is in terms of cavitons formed near the reflection height of the pump wave. It should be noted here that the numerical simulations /10,41/ were carried out for conditions under which the growth rate of the OTSI was greater than the growth rate of the PDI. Their cavitons resulted from the nonlinear saturation of the OTSI. Figure 1 shows that near the reflection height, for strong pumps the growth rate of the OTSI is indeed greater than the growth rate of the PDI but according to Figure 2 the opposite is likely to be true even for strong pumps at the height where the dispersion relation is satisfied in the unperturbed medium by the Langmuir waves detectable by the 430 MHz radar.

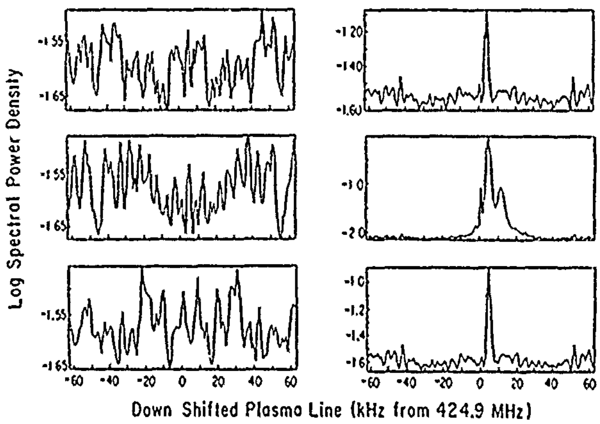


Fig. 3. Strong power spectra of the enhanced plasma line for six different heights 1.2 km apart. The spectrum at top left corresponds to the smallest height, the spectrum at bottom right to the greatest height. A large number of spectra were averaged; the strongest spectrum was always placed in the second greatest height bin (middle right). The observations started at 1807 on 24 January 1986.

If it is accepted that most of the power in the spectrum of the observed enhanced plasma line originates in cavitons then some recent spectral observations with height discrimination /47/ are of considerable interest. Figure 3 shows spectra obtained in this manner during 1807-1822 on January 24, 1986, for 6 heights 1.2 km apart. Without giving all the details of the technique here, the main conclusion was that the usual features of the enhanced plasma line spectrum, the PDI line, its weak cascade and the OTSI line, all come from the same height region which is about 1 km wide. If this result is combined with the results of Birkmayer et al. /43/ then the conclusion is almost inescapable that all three features are generated in the same cavitons. The observed width of the OTSI line of 20 - 60 Hz, as shown for example in Figure 7 of /21/, suggests that the cavitons have life times of about 16 - 50 ms.

Summing up, there is increasing experimental evidence that cavitons are formed in ionospheric heating experiments, using a strong pump. It seems that at least at wave lengths of 35 cm during some stage of their "life" the PDI and its cascade as well as the OTSI are excited inside the cavitons, the excitation of the PDI being by far the most powerful. None of the present theories or numerical simulations predict such properties of a caviton; further theoretical work is very desirable.

## 6. ELECTRON ACCELERATION IN IONOSPHERIC HEATING EXPERIMENTS

Early Platteville observations of the 630 nm airglow line /48,49/ suggested collisional excitation by electrons accelerated to energies greater than 2 eV by parametrically excited Langmuir waves. Carlson et al. /50/ observed (in 1972) the accelerated electrons indirectly through their enhancement of the natural plasma line at night when the photoelectrons were absent. Perkins and Salpeter /51/ formulated the theory of such enhancements; Yngvesson and Perkins /52/ applied the theory to enhancement of the natural plasma line by photoelectrons.

Observations of enhancements of the natural plasma line spectrum over a bandwidth of 500 kHz at night are shown in Figure 10 of /21/. The pump wave was cycled 2 s on 3 s off and spectra were obtained every 0.5 s. The successive spectra clearly show that the appearance and the disappearance of the enhancement had time constants of the order of hundreds of milliseconds. This was in agreement with the ideas expressed by Carlson et al. /50/ and by Gurevich et al. /42/ that an accelerated electron is scattered in repeated collisions with neutral particles and could even return several times to the acceleration region to interact with the Langmuir waves there. Gurevich et al. /42/ called this process multiple acceleration and stressed the possible role of Langmuir waves in cavitons in the acceleration process.

Sulzer and Fejer /53/ have repeated the experiment leading to Figure 10 of /21/ with a better time resolution of 100 ms, both at night in the absence of photoelectrons and in daytime in the presence of photoelectrons. The improved time resolution necessitates a different method of display, in which the power in different parts of the 500 kHz wide spectrum is shown as a function of the time.

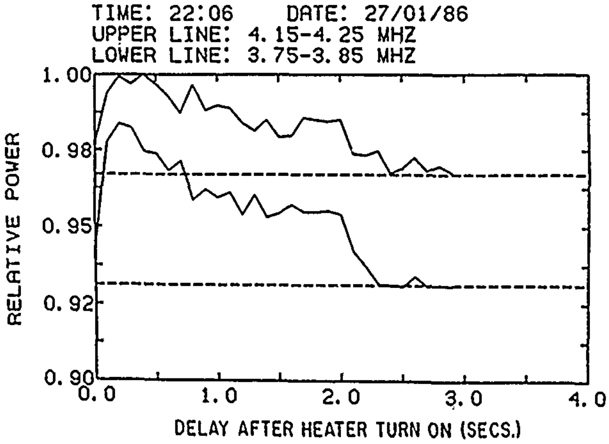


Fig. 4. The relative powers in the natural plasma line in the 4.15 - 4.25 MHz and 3.75 - 3.85 MHz downshifted Doppler frequency bands as functions of the delay time after heater turn on. The heater was turned off after 2 second. The heater frequency was 3.175 MHz.

Figure 4 shows the power in the 3.75 - 3.85 MHz and the 4.15 - 4.25 MHz Doppler frequency bands of the downshifted natural plasma line at night as a function of the time after the pump was switched on, integrated over a large number of 2 s on, 3 s off pump cycles during 15 minutes following 2206 on 27 January, 1986. In the 3.75 - 3.85 MHz band the largest enhancement of 6% above system noise occurs 0.25 s after switching on the pump wave. In the 4.15 - 4.25 MHz band the enhancement is somewhat less and reaches its maximum somewhat later.

An interesting effect is the decrease of the enhancement, after the initial maximum, to a steady value of about half the maximum in a second or less. This is strongly reminiscent of the overshoot /54/ of the enhanced plasma line, observed with the 430 MHz radar.

Figure 5 shows the same kind of data as Figure 4 for the afternoon of 20 January, 1986, in the presence of photoelectrons. The pump frequency was 5.1 MHz and the downshifted natural plasma line was observed in the 5.25 - 5.75 MHz Doppler band. The enhanced plasma line with Doppler shifts close to 5.1 MHz was aliased into the observed band at 5.6 MHz without too much attenuation by the filter; the difference of 0.5 MHz is the reciprocal of the sampling time of 2 microseconds.

The power in the aliased enhanced plasma line is shown at the top of Figure 5; it clearly displays the overshoot effect. The power in the natural plasma line in the 5.25 - 5.35 MHz and in in the 5.65 - 5.75 MHz Doppler bands is shown in the center and at the bottom of Figure 5. The overshoot in the 5.25 - 5.35 MHz band closely resembles the overshoot in the enhanced plasma line; the maximum enhancement is about 25% and appears without measurable delay. The enhancement of 25% is over the natural plasma line in the presence of photoelectrons which itself exceeded the system noise by a factor of the order of 50. The maximum enhancement of the natural plasma line was therefore 12.5 times above system noise, about 200 times greater than the enhancement of 6% at night. It is therefore extremely unlikely that the enhancement is due to the acceleration of the thermal electrons. A modification of the distribution function of photoelectrons is a far more likely cause of the enhancement and it explains the short delay time. Ultimately this modification of the rather steep energy spectrum of photoelectrons must have an effect on the ionospheric electron density.

The power in the 5.65 - 5.75 MHz band shows a slightly smaller enhancement with a measurable delay of the order of 100 ms. This is understandable because the backscatter in that band comes from a height that is further from the acceleration region where the plasma frequency is near 5.1 MHz.

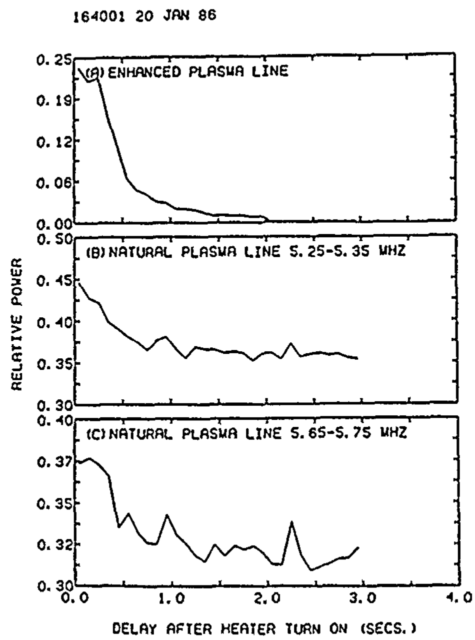


Fig. 5. The relative power in the photoelectron enhanced natural plasma line in the 5.25 - 5.35 and the 5.65 - 5.75 MHz downshifted Doppler frequency bands as a function of the delay time after heater turn on. The heater was turned off after 2 seconds. The heater frequency was 5.1 MHz.

## 7. CONCLUDING REMARKS

It is hoped that this brief and incomplete review demonstrates that there has been a considerable increase in our understanding of the physical processes involved in ionospheric heating. Among recent highlights in this increased understanding is the knowledge that the main features of the enhanced plasma line for strong pumps almost certainly are manifestations of backscatter from Langmuir waves trapped in localized depressions of the plasma density near the reflection region of the pump wave. Previously the backscatter was thought to come from the lower height where the dispersion relation of the detected Langmuir waves was satisfied in the background plasma rather than in localized depressions. The localized depressions together with the Langmuir waves (not only those detected by the radar) whose ponderomotive force maintains the depressions, are usually called cavitons. The observed width of the OTSI feature in the spectrum of the enhanced plasma line suggests a lifetime of 16 - 50 ms for the cavitons.

Another highlight is the increased knowledge of the electron acceleration process at night and of the strong modification in the distribution function of photoelectrons in daytime during ionospheric heating experiments. The well known overshoot in the enhanced plasma line appears to exert a strong influence on the evolution of the accelerated electron fluxes at night and an even stronger influence on the modification in the photoelectron fluxes in daytime. The overshoot of the enhanced plasma line is, however, still only partially understood.

Further observations will clearly be necessary to supplement some of the initial and preliminary results presented here. In addition considerable theoretical and numerical work is needed to explain the observed properties of cavitons in ionospheric heating experiments. Quantitative comparisons of the observed suprathermal electron fluxes with existing theories and additional work on the theory of the temporal evolution of the suprathermal electron fluxes are also needed.

## ACKNOWLEDGEMENTS

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## APPENDIX. GROWTH RATES OF THE PDI AND THE OTSI

The electrostatic dispersion relation of waves in a plasma in the presence of a uniform oscillating electric field $\underset{\sim}{E}_0$ of angular frequency $\omega_0$ is given in the absence of an external magnetic field by

$$-\frac{2k^2h_i^2}{Z'(\omega/kv_{thi})} + F(k,\omega) + \frac{1}{4}(\underset{\sim}{k}\cdot\underset{\sim}{d})^2[F(k,\omega+\omega_0)+F(k,\omega-\omega_0)] = 0 \tag{1}$$

$$\text{where}\quad F(k,\omega) = [1-\frac{2k^2h_e^2}{Z'(\omega/kv_{the})} + i\frac{\omega_r}{|\omega_r|}\frac{\nu_{ei}}{\omega_p}]^{-1}, \tag{2}$$

$$\omega = \omega_r + i\gamma\,, \tag{3}$$

$$\underset{\sim}{d} = c\underset{\sim}{E}_0/m\omega_0^2$$

$$v_{the,i} = (KT_{e,i}/m_{e,i})^{1/2} \tag{4}$$

and $$h_{e,i} = (\epsilon_0 KT_{e,i}/Ne^2)^{1/2}\,. \tag{5}$$

In the above equations, $T_{e,i}$ is the temperature and $m_{e,i}$ the mass of electrons or singly charged ions, e is the electronic charge. N is the number density of electrons and K is Boltzmann's constant.

The ratio of $\omega_0$ to the plasma frequency $\omega_p = (Ne^2/\epsilon_0 m)^{1/2}$ is taken as 1.0017 in Figure 1 and as 1.0084 in Figure 2. In both Figures $\nu_{ei}/\omega_p = 8\times10^{-6}$, $T_e = T_i = 1000$K, $N = 3\times10^{11}\,m^{-3}$ were assumed. The ions were taken to be atomic oxygen ions.

The value of $\gamma$ for a given value of $E_0$ was obtained from the dispersion relation (1) which was solved for $\omega$ for different values of k. Two maxima of $\gamma$ were then found for two different values of k. One of these corresponded to the OTSI and the other to the PDI. This was done for different values of $E_0$; the results are shown by Figures 1 and 2 which show $\gamma$ as a function of $E_0$.

ATTACHMENT 5



# AGARD

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# IONOSPHERIC STRUCTURE AND VARIABILITY ON A GLOBAL SCALE AND INTERACTIONS WITH ATMOSPHERE AND MAGNETOSPHERE

NORTH ATLANTIC TREATY ORGANIZATION

# IONOSPHERIC IRREGULARITIES DUE TO POWERFUL HF RADIO TRANSMISSIONS

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SUMMARY

It has been known for some time that sufficiently powerful HF radio transmissions produce a great variety of ionospheric irregularities. Ionospheric modification facilities with effective radiated powers of the order of 100 MW directed toward the ionosphere have been used for the study of such irregularities since 1970. Such man-made irregularities have been employed to establish experimental scatter communications links. Very powerful short wave broadcast transmitters must also produce man-made irregularities which affect the ionospheric propagation of short waves.

All aspects of the physical phenomena which play a role in the production of ionospheric irregularities by powerful HF transmissions, are discussed. These include thermal self-focusing of radio waves, formation of short-scale field-aligned irregularities by a thermal parametric instability in which the scattering of the HF pump wave by the irregularities into Langmuir waves plays an important role, and those parametric instabilities in which the ponderomotive force dominates over thermal forces. The latter two parametric instabilities can lead to the acceleration of electrons to energies of tens of electron volts. Such accelerated electrons can produce artificial airglow and also additional ionization which under certain conditions could be significant. In their strongly nonlinear stage parametric instabilities can lead to the formation of localized electron density depletions (cavitons) maintained by the ponderomotive force of Langmuir waves trapped in them.

## 1. INTRODUCTION

Powerful HF radio transmissions radiated by modern ionospheric modification facilities produce irregularities by a process of stimulated scattering. The irregularities scatter the radio wave into other high frequency waves which could be electrostatic (Langmuir waves) or electromagnetic (other radio waves). These other high frequency waves interact with the original powerful radio wave via a nonlinear force which by feedback causes the irregularities to grow (stimulates them), starting from their initial thermal level. The growth of the irregularities is thus due to a type of plasma instability which goes by the names of either stimulated scattering or parametric instability.

The irregularities could be independent of time or they could change "slowly", the corresponding frequencies being very much smaller than that of the original powerful radio wave. In this sense an assembly of ion acoustic waves will also be referred to as irregularities. It is in this more general sense that ionospheric irregularities due to powerful HF radio transmissions will be discussed here.

It is usually easiest to consider first the linear theory of a parametric instability in a homogeneous medium; in practice even an inhomogeneous medium can often be approximated locally by a homogeneous medium. Such a theory considers the initial stage when the growing irregularities are of small amplitude; then their growth and their possibly oscillatory nature can be treated by Fourier analysis. In many cases a wavelike Fourier component could have zero frequency and then the irregularity is simply a spatially periodic density perturbation of small amplitude. A linear mathematical formulation of the stimulated scattering process described above then leads to a dispersion relation which for a real wave vector $\underline{k}$ of the assumed wavelike irregularity leads to a complex angular frequency $\omega$.

The dispersion relation depends on the strength of the original powerful radio wave, usually called the pump wave. For a sufficiently weak pump wave all the solutions of the dispersion relation are damped waves if the plasma is stable. As the strength of the pump wave is increased, eventually for a certain wave vector $\underline{k}$ the dispersion relation leads to a real angular frequency; the condition for this is called the linear threshold condition. When the strength of the pump wave is above its threshold strength then the linear dispersion relation results in a positive growth rate for a range of values of the wave vector $\underline{k}$ of the assumed small irregularity. The growth rates thus obtained are called linear growth rates and are only valid for small amplitudes.

Linear theory gives no information on the mechanism that eventually stops the growth and results in the so called saturation spectrum of the irregularities. The nonlinear theories of the saturation of parametric instabilities are less well developed than the linear theories on account of their more difficult nature but some progress has been made.

Each of the following sections will deal with one of the different parametric instabilities excited by a powerful radio wave. Their associated low or zero frequency

irregularities and the high frequency waves into which the irregularities scatter the pump wave will be discussed from both a theoretical and an observational point of view. Although in reality the different parametric instabilities are not excited completely independently of each other, it will be convenient to deal with them one at a time without ignoring their interdependence.

## 2. THE OSCILLATING TWO STREAM INSTABILITY

This parametric instability [1]-[3], usually abbreviated OTSI, was the first one whose excitation in ionospheric modification experiments was predicted theoretically [4]. In this instability the electromagnetic pump wave of ordinary polarization causes the simultaneous growth of a spatially periodic non-oscillatory density perturbation and a standing Langmuir wave of about the same wavelength, both being very much smaller than the wavelength of the pump. Since the Langmuir wave is the result of scattering of the pump wave by the density perturbation, the frequency of the Langmuir wave is equal to the frequency of the pump. In the linear theory this instability and the parametric decay instability, discussed in the next section, represent two solutions of the same dispersion relation. A brief outline of the theory will therefore be postponed; it will form part of the next section. It should be remarked already here, however, that these two instabilities can only be excited by a pump wave of ordinary polarization at frequencies below the maximum plasma frequency of the ionosphere; the extraordinary wave is reflected below the height where lightly damped Langmuir waves can exist. In both instabilities the nonlinear force completing the feedback loop is the ponderomotive force.

The OTSI has been detected at Arecibo [5], [6] and later at Tromso [7] by observing the upshifted or downshifted spectra of radar backscatter by its Langmuir waves. In those observations a radar pulse whose length was of the order of 1 ms was used. The radar echo was then coherently sampled, say, every 2 microseconds. The complex digital Fourier transform of the sample values was then taken and the absolute values squared to obtain the power spectrum with a frequency resolution of about 1 kHz, the reciprocal of the pulse length of 1ms. Such spectra, which in addition to the OTSI also show the excitation of the PDI (parametric decay instability), will be shown in the next section; they are usually called spectra of the enhanced plasma line, to differentiate them from the plasma line of incoherent scatter.

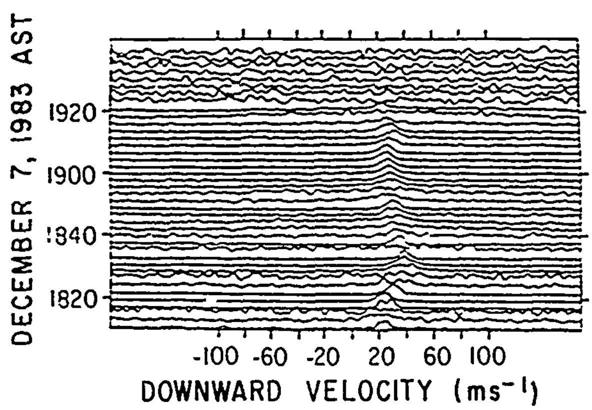


Figure 1. Spectra of the OTSI line over a bandwidth of 1 kHz, calibrated in line-of-sight drift velocity, for different local times.

In this section 1 kHz wide spectra, obtained by using much shorter radar pulses transmitted coherently every millisecond and by sampling a large number of consecutive scatter echoes, will be shown. Such spectra have a much better frequency resolution, determined by the reciprocal of the the duration of the sequence of short pulses. Figure 1 (Figure 7 of [8])shows such 1 kHz wide spectra taken every minute for about an hour. As will be seen in the next section, the spectra of the PDI are very much wider than 1kHz and appear aliased as noise in the spectra of Figure 1. Those spectra therefore only display the (upshifted) radar backscatter from the Langmuir waves of the OTSI which in the absence of ionospheric drifts would have a frequency of 435.1 MHz, the sum of the radar frequency of 430 MHz and the HF transmitter frequency of 5.1 MHz. The frequency of the Langmuir waves of the OTSI are predicted to be equal to the frequency of the HF pump wave in a reference frame drifting with the electron gas; the Doppler shift due to that drift velocity causes the frequency of the upshifted OTSI line to differ from 535.1 MHz, marked 0 m/s on Figure 1 whose 1kHz wide spectra are calibrated in line-of-sight drift velocity. The maximum plasma frequency of the ionosphere sank below the pump frequency of 5.1 MHz at about 1920 AST and the spectra obtained after that time do not show the OTSI scatter echo.

Figure 1 shows that the line-of-sight electron drift velocity may be determined from observations of the OTSI. Observations of the ion line of incoherent scatter are known to yield the line-of-sight ion drift velocity. It should therefore be possible

to determine the line of sight component of the current density vector from the combination of those two observations.

## 3. THE PARAMETRIC DECAY INSTABILITY

In the PDI the generated low frequency wave is an ion acoustic wave and the generated high frequency wave is a Langmuir wave whose frequency is less than the pump frequency by the frequency of the ion acoustic wave. This follows from the matching relations

$$\omega_0 = \omega_1 + \omega_2 \qquad (1)$$

$$\underline{k}_0 = \underline{k}_1 + \underline{k}_2 \qquad (2)$$

satisfied by the pump wave and the two generated (daughter) waves in parametric instabilities of this type.

The dispersion relation resulting from the linear theory was derived, for example, in [9]. The feedback to the low frequency wave results in this case from the ponderomotive force. The growth rate resulting from that dispersion relation is largest when the propagation vector is parallel to the pump electric field. For that direction the growth rate has two well separated maxima as a function of the wave number, corresponding to the PDI and the OTSI. Although the threshold pump electric field is slightly lower for the PDI than for the OTSI, both being slightly below 0.2 V/m , Figures 1 and 2 of [10], based on computations by Erhan Kudeki, show that for typical ionospheric parameters the linear growth rate of the OTSI exceeds that of the PDI for pump electric fields greater than 0.5 V/m when X = 0.983, and for pump electric fields greater than 0.9 V/m when X = 0.997 where X is the square of the ratio of the plasma frequency to the pump frequency. Thus for full pump power of a typical ionospheric modification facility the linear growth rate of the OTSI certainly exceeds that of the PDI at the first peak of the Airy pattern but probably not at the lower height where Langmuir waves detected by the 430 MHz radar at Arecibo satisfy the dispersion relation in the unpertubed ionosphere.

Saturation spectra predicted by weak turbulence theory were computed in [11] and [12]. The results of those computations show that the Langmuir waves of the parametric decay instability, excited first linearly by the pump, eventually decay further parametrically into Langmuir waves going in the opposite direction. Several additional similar decays produce a whole cascade of Langmuir waves, the frequency difference between the pump and the first member of the cascade being half of the frequency difference between neighboring members of the cascade. The propagation vectors of the excited Langmuir waves form angles of less than about 25$^{\circ}$ with the pump electric field which for the ordinary wave is close to the direction of the geomagnetic field near the height of reflection.

The Arecibo radar beam forms an angle of 45$^{\circ}$ with the geomagnetic field and therefore according to theory the radar should not detect the parametrically excited Langmuir waves directly. It should detect ([12], [13]), however, the much weaker Langmuir waves into which the parametrically excited Langmuir waves and the pump wave are scattered by the ion acoustic waves in thermal equilibrium (which are also responsible for incoherent scatter). Even the Langmuir waves into which the pump wave slightly below threshold strength is scattered by the thermal ion acoustic waves, are still well above the thermal level of Langmuir waves [14].

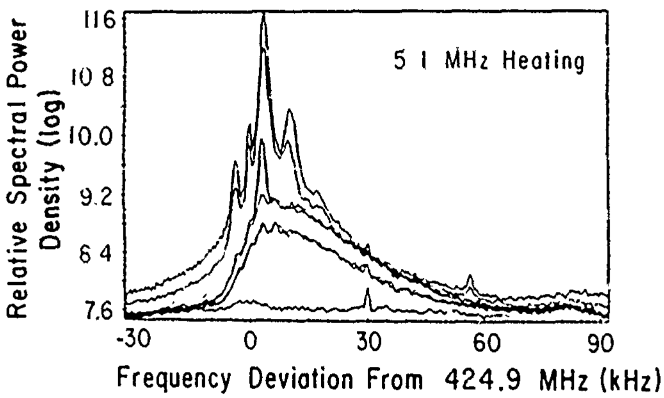


Figure 2. Several spectra of the enhanced plasma line obtained by scanning the angle of the 430 MHz radar beam while keeping the elevation angle constant at 3.5$^{\circ}$ from vertical. All the spectra were obtained within a single scan.

Figure 2 (Figure 9 of [8]) shows some downshifted enhanced plasma line spectra from the F-region above Arecibo, ranging from below threshold conditions to full pump strength.

after the pump is switched on. An example of the overshoot is shown by Figure 3 with a somewhat better temporal resolution than in the observations of [35]. Graham and Fejer [36] suggested that the overshoot is caused by the absorption suffered by the pump wave near the height where its frequency is close to the upper hybrid frequency and the field aligned irregularities scatter the pump wave into Langmuir waves. Fejer and Kopka [37] demonstrated the absorption of the reflected pump wave of the Tromso heating facility, both by this mechanism and by the excitation of the parametric decay instability; however Djuth and Gonzales [38] showed that at Arecibo such absorption is sometimes too small to be observed and can not explain the observed overshoot. Other Arecibo observations [19] suggest that even on such occasions the growth of a plasma instability, presumably that responsible for the short-scale field-aligned irregularities, is the cause of the overshoot.

It should be noted that both the thermal parametric instability discussed in this section and the two striction type parametric instabilities, the PDI and the OTSI, discussed in the last section, generate Langmuir waves which can accelerate electrons. Collisional excitation of the 630 nm and 557.7 nm oxygen lines by such electrons was observed very early [39]). The question arises whether electron acceleration is mainly due to the Langmuir waves of the thermal parametric instability or of the striction parametric instabilities. Workers in the USSR favor the thermal parametric instability [40]. Fejer and Sulzer [41] observed the accelerated electrons by observing the enhancement in the natural plasma line caused by them at night. They show that electron acceleration is strongest before the growth of the thermal parametric instability and must therefore be caused by the Langmuir waves of the striction parametric instability. It seems likely that the striction parametric instabilities play a larger role in electron acceleration at lower latitudes than the thermal parametric instability but the latter may well be more important at higher latitudes with the exception of the first second or so after the heating transmissions are switched on.

## 5. THERMAL SELF-FOCUSING

This instability was one of the first physical processes discovered when the Platteville facility started operation [42]. Within seconds of switching on the modifying HF transmissions the ionograms showed the presence of spread-F although the full extent of spread-F took some minutes to develop. The irregularities produced by the instability were also investigated by the observation of enhanced scintillation of signals observed from satellite transmitters [43], [44] and from radio stars [45]-[48]). Another method of investigating the irregularities is the observation of the fading of the power in the enhanced plasma line on time scales of the order of 10 s [49]-[51]. The density variations were also measured directly by satellite in situ probes [51]. These observations show the presence of artificial ionospheric irregularities over a scale length range of a few kilometers to tens of meters. Figure 4 (Figure 4 of [51]) shows the density perturbations measured by the satellite and also illustrates its path through the estimated heater beam.

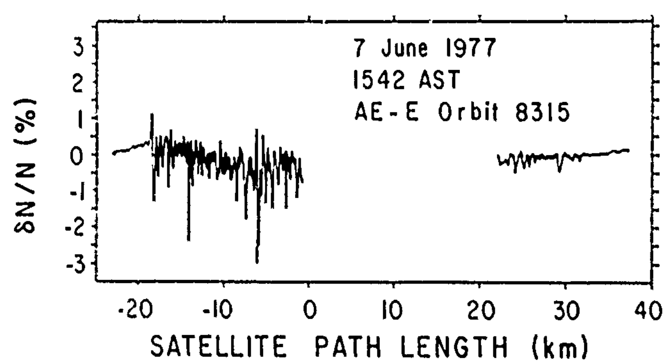


Figure 4. Detrended satellite observations of density fluctuations in the heated region. The origin is the point along the orbital path which is due north of Arecibo. The data gap results from the fact that the satellite operates 3 s on 3 s off in this mode.

The basic idea of thermal self-focusing is rather simple. Initial small plasma density perturbations cause focusing and defocusing of the heating wave. The focusing in the density depletions causes enhanced heating and further depletion, allowing the perturbations to grow. The theories are in a sense simpler when the heating wave penetrates the ionosphere [52]; even the nonlinear development of self-focusing has been followed for that case by a numerical simulation [53]. The case of self-focusing of a reflected heating wave was treated in [54]-[56]. The inhomogeneity of the ionosphere plays a very important role in all these theories.

Self-focusing is essentially a modulational instability. It can be considered as stimulated scattering of the pump wave by the irregularities into electromagnetic waves; the feedback is thermal rather than ponderomotive in nature. It will be recalled that the instability discussed in the last section could be regarded as stimulated scattering by the irregularities into Langmuir waves rather than electromagnetic waves.

The self-focusing of an obliquely incident pump wave was considered [57]) and it was pointed out that powerful short wave stations almost certainly excite the self-focusing instability and therefore must be a source of ionospheric irregularities.

## 6. CONCLUSIONS

An attempt was made to describe the different ways in which ionospheric irregularities can be produced by powerful radio transmissions. No attempt was made to describe all the effects produced by such radio transmissions. One important omitted topic was the generation of VLF, ELF and ULF waves by modulating the auroral electrojet currents. Another omitted topic was that of ionospheric cross-modulation. The most important irregularities from the point of view of this Symposium are probably the short scale field-aligned irregularities discussed in section 4 and the much longer scale irregularities produced by self-focusing and discussed in section 5.

## ACKNOWLEDGEMENTS

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## DISCUSSION

**K.Rawer**

*Question of clarification:* In the context of PDI is what you call "ion-acoustic wave" an acoustic wave (in the ion gas) of rather high frequency which would then not be followed by the electrons so that electric fields should simultaneously occur (this type is-unfortunately-often called "electrostatic wave") or is it lower frequency acoustic or even gravity waves?

**Author's Reply**

The ion-acoustic waves of the PDI are of the same type as those responsible for incoherent backscatter. The ions and electrons "move" together and a small electric field assures quasi-neutrality. This electric field does increase the propagation velocity of the wave and this has the effect of reducing Landau damping (fewer ions are in synchronism with the wave).

**R.Showen**

You said that the radial electron velocity can be measured by the OTSI plasma line. Have any geophysical results from Arecibo or EISCAT appeared which use the OTSI enhancement?

Are the measured electron velocities the same for upshifted and downshifted lines?

**Author's Reply**

There have not been enough observations for a detailed geophysical interpretation. The data shown have not been published so far, but earlier data of poorer quality have been published in J.A.T.P. (*Fejer et al.*, 1985). The method of measuring the ion drift velocity has been greatly improved since that time (*Sulzer*, 1986).

The electron velocities have not been measured simultaneously for the upshifted and downshifted lines: it would be very surprising if they were different.

**G.Rostoker**

Over what height range can you use line-of-sight electron (DTSI) and ion velocities to infer line or sight current flow?

Also, is there any concern that the heater will perturb the region in which you infer the current flow making it unrepresentative of the surrounding unperturbed environment?

**Author's Reply**

The measurement of the line-of-sight drift velocity of electrons is made for the height where the heating frequency is close to the local plasma frequency. The ion velocity is measured for a somewhat greater height range.

Varying the heating power was found to have no influence on the measured drift velocity within the accuracy of the observations.

**P.Vila**

Are the photoelectrons which arise in the Shirp experiment (Arecibo) natural, or produced by the heating transmitter?

**Author's Reply**

They are natural; The photoelectrons in the Shirp experiments are only in the daytime. Their energies lie in the 10-30 eV energy range. They are not produced by the heating transmitter, but there is evidence that their distribution function is modified by the heating transmitter (*Fejer and Subaer*, 1987).

ATTACHMENT 6

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# Simultaneous observations of the enhanced plasma line and of the reflected HF wave at Arecibo

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**Abstract**—A suitably devised pulsing sequence of the powerful HF transmissions radiated towards the ionosphere below the penetration frequency made it possible to separate the attenuation of the reflected HF wave due to thermal and to ponderomotive type parametric instabilities. The separation was possible on account of the different growth times of the thermal and ponderomotive type parametric instabilities. At the same time the power in the 430 MHz enhanced plasma line was recorded.

The results show that previously accepted explanations of the overshoot in the 430 MHz enhanced plasma line for 5.3 MHz HF transmissions are invalid. A strong overshoot was observed but the attenuation of the powerful HF wave was too small to be observed. For 3.175 MHz HF transmissions substantial attenuation was observed on both time scales.

## 1. INTRODUCTION

Among the many interesting and unexpected phenomena observed very soon after the completion of the high power HF transmitting facility for the modification of the ionosphere at Platteville, Colorado (UTLAUT, 1970) was the reduced strength of the $F$-region echo from diagnostic HF pulse transmissions within about a second after the start of the high power HF transmissions (COHEN and WHITEHEAD, 1970). These results could not be explained by a simple modification of the electron densities and temperature of the $F$-region.

Observations of transient variations in the intensity of the reflected modifying HF wave were made by FEJER and KOPKA (1981) using the joint German-Norwegian ionospheric modification facility near Tromso, Norway. They observed first a very rapid decrease in intensity on the time scale of a millisecond and then a slower further decrease on the time scale of a second. They attributed the rapid decrease to the excitation of ponderomotive type parametric instabilities (FEJER and LEER, 1972) and the slower decrease to the excitation of the thermal parametric instability or stimulated scattering by field-aligned irregularities into Langmuir waves (DAS and FEJER, 1979). The former were originally invoked to explain the enhanced plasma line observed with the 430 MHz radar at Arecibo (WONG and TAYLOR, 1971; CARLSON *et al.*, 1972), the latter to explain the observations (FIALER, 1974) of backscatter and forward scatter of radio waves by short-scale field-aligned irregularities in the $F$-region above Platteville.

One of the most persistent properties of the 430 MHz enhanced plasma line (enhanced radar backscatter by Langmuir waves due to powerful HF transmissions) observed at Arecibo is its drop in intensity to a lower steady state level in about a second after attaining an initial maximum in less than one tenth of a second after switching on the HF transmitters. This so-called overshoot (SHOWEN and KIM, 1978) has been attributed to attenuation of the heating wave which is being scattered by the short-scale field-aligned irregularities into Langmuir waves (GRAHAM and FEJER, 1976). This explanation of the overshoot has been questioned by DJUTH *et al.* (1986) who observed strong overshoots in the enhanced plasma line without any measurable change in the strength of the observed ionospherically reflected powerful HF wave at Arecibo.

The experiment described here was designed to determine from observations of the reflected HF wave at Arecibo separately the fraction of the HF power incident on the ionosphere that goes into the generation of ponderomotive parametric instabilities with their millisecond time constant and the fraction that goes into the generation of the thermal parametric instability with its time constant of the order of a second. This was achieved by cycling the HF transmitters 40 ms on, 10 ms off for 2 s and then keeping them switched off for several seconds before the next cycling period of 2 s duration. The 10 ms off-period allowed the waves generated by the ponderomotive parametric instabilities with their millisecond time constant to decay completely without affecting the thermal parametric instability whose short-scale field-aligned irregularities decay according to scatter observations (FIALER, 1974) with the much larger time constant of about a second.

Besides recording the power of the reflected HF wave at the Arecibo Observatory, the transmitted HF power was recorded at the Islote transmitting site 17 miles north-east of the Arecibo Observatory. In addition the power in the 430 MHz enhanced plasma line, integrated over each 40 ms on-period, was also recorded.

The experiment was carried out for the two HF frequencies of 5.1 MHz and 3.175 MHz. It has been known for some years (FEJER et al., 1985) that for HF transmissions at 3.175 MHz the 430 MHz enhanced plasma line is seen for only a few hundred milliseconds after switching on the HF transmitters and then only after a sufficiently long off-period. One possible explanation is the greater Landau damping of the Langmuir waves that satisfy the Bragg conditions for the 430 MHz radar (YNGVESSON AND PERKINS, 1968) for the lower plasma densities corresponding to the lower HF frequency and for the increased ionospheric electron temperature resulting from a few hundred milliseconds of HF transmissions. For the higher plasma densities, corresponding to 5.1 MHz HF transmissions, the Landau damping of Langmuir waves

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$f_{HF} = 5.13$ MHz
ERP = 80 MW ( 2 s ON, 2 s OFF )

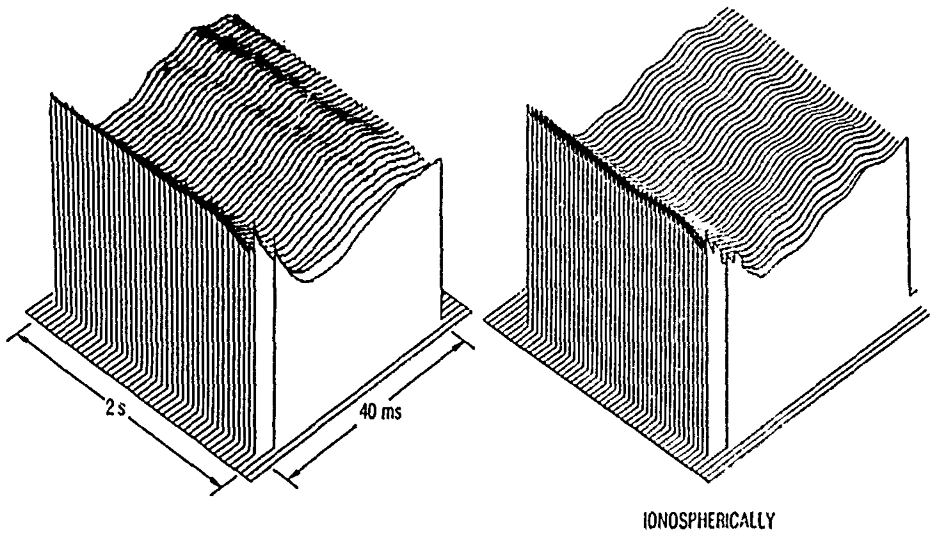


Fig. 1. Three-dimensional representation for 5.13 MHz HF transmissions of the temporal variation of the transmitted and ionospherically reflected power averaged over 20 cycling periods of 2 s duration. Due to a small timing error the cycling periods of 2 s duration started about 2 ms too late; the first transmitted pulse was therefore only about 38 ms long and an additional 2 ms long pulse was transmitted at the end.

detectable by the 430 MHz radar, propagating in a nearly uniform thermal plasma at typical $F$-region temperatures can always be neglected. For these reasons the several second long off-period mentioned earlier was chosen to have a length of 8 s for 3.175 MHz transmissions but only a length of 2 s for 5.1 MHz transmissions. The longer off-period of 8 s allows the enhanced electron temperature responsible for the increased Landau damping to drop sufficiently for the excitation of ponderomotive parametric instabilities during the 3.175 MHz HF transmissions, for the early part of the on-period of 2 s.

## 2. OBSERVATIONS

The observations were carried out on 1 March, 1985 with an equivalent radiated HF power (ERP) of 80 MW in the O mode, first using a frequency of 5.13 MHz and somewhat later 3.175 MHz. The receiver for the reflected HF wave used a simple dipole antenna at the focus of the 305 m spherical reflector. The power at the output of this receiver was recorded and will for brevity be referred to as the ionospherically reflected power.

Figure 1 illustrates for 5.13 MHz HF transmissions the time dependence of the transmitted power and of the ionospherically reflected power, averaged over 20 cycling periods of 2 s length; two separate arbitrary power scales are used for the transmitted and the reflected power. The 40 ms on, 10 ms off cycling was explained in the previous section. Note the large oscillations of the transmitted power during the 40 ms transmission periods; they are caused by oscillations of the smoothing L-C circuits in the transmitters. From records of both the transmitted and the ionospherically reflected power it was in principle possible to determine the temporal variations of ionospheric attenuation. Note also the effect of multiple ionospheric reflections in Fig. 1, similar to the effects seen by FEJER and KOPKA (1981). Figure 1 for 5.13 MHz heating and the similar three-dimensional representation of the raw data by Fig. 2 for 3.175 MHz heating are not very convenient for quantitative interpretation. A more convenient representation of

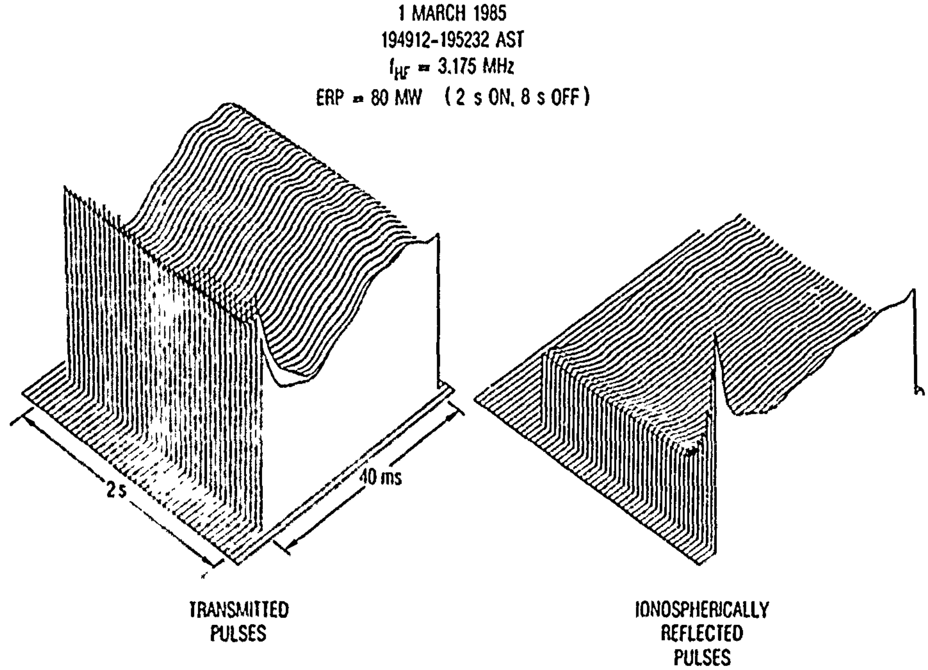


Fig. 2. Three-dimensional representation for 3.175 MHz HF transmissions of the temporal variations of the transmitted and ionospherically reflected power averaged over 20 cyling periods of 2 s duration. There was no timing error for these transmissions. Note, however, that there are forty 40 ms long records of the "transmitted pulses" but only thirty-nine 40 ms long records of the "received pulses". Due to a data-taking error the ionospherically reflected power was not recorded for the first 40 ms long transmitted pulse.

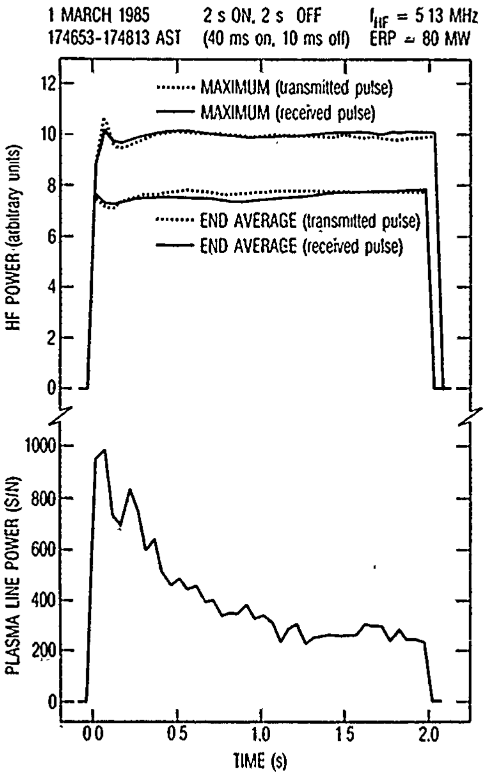


Fig. 3. Temporal variations for 5.3 MHz HF transmissions of the maximum and end average transmitted and ionospherically reflected powers and of the plasma line power averaged over 20 cycling periods of 2 s duration.

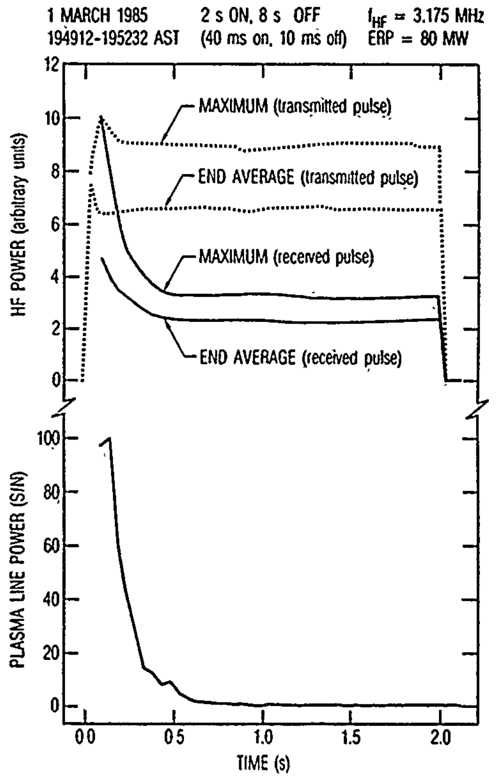


Fig. 4. Temporal variation for 3.175 MHz HF transmissions of the maximum and end average transmitted and ionospherically received powers and of the plasma line power averaged over 20 cycling periods of 2 s duration. Note that due to the error mentioned in the caption to Fig. 2 the values of the received HF power (maximum and end average) and of the plasma line power are missing for the first 40 ms long transmitted pulse.

the same data is provided by Figs. 3 and 4. In those figures each 40 ms on-period is represented by the maximum value of the power and by its end-average value during the last 15 ms, for both the transmitted and the ionospherically reflected power. Those four values are shown as a function of time every 50 ms over the 2 s cycling period at the top parts of Fig. 3 for 5.3 MHz and of Fig. 4 for 3.175 MHz. Also shown at the bottom of Figs. 3 and 4 is the power in the enhanced plasma line, integrated over each 40 ms on-period. The very short spikes seen at the beginning of the 40 ms on-periods in the recorded transmitted power in Figs. 1 and 2 were caused by the transient response of the recorder; they were omitted in obtaining the maximum values of the transmitted power for each 40 ms on-period in Figs. 3 and 4. The effects of the timing error of about 2 ms in the 5.3 MHz HF transmissions visible in Fig. 1 and explained in its caption resulted in additional pulse of 2 ms length which was ignored in obtaining Fig. 3.

Figure 3 shows no change in attenuation of the reflected 5.3 MHz HF wave on either the millisecond or on the second time scale. This is in sharp contrast with Fig. 4 where for convenience the initial maxima of the transmitted and reflected power were made to coincide for the second 40 ms on-period. It is explained in the caption to Fig. 2 that due to an error in data-taking the reflected power (and the plasma line power) for the first 40 ms on-period were not recorded. At the beginning of the last 40 ms on-period the ratio of the transmitted to the received initial maximum powers is 2.71, corresponding to 4.3 db attenuation at that time. Near the end of the second 40 ms on-period the ratio of the transmitted to the received end average powers is 1.38, corresponding to an attenuation of 1.4 db which must be caused almost entirely by the excitation of ponderomotive type parametric instabilities. Near the end of the last 40 ms on-period the ratio of the transmitted and received end

average power is 2.74, corresponding to 4.4 db attenuation. The difference of 4.4–4.3 = 0.1 db is that part of the 4.4 db attenuation due to ponderomotive type parametric instabilities near the end of 2 s cycling sequence.

The bottom part of Fig. 3 shows that in a little more than the first second the plasma line intensity drops by a factor of about 4, there is no further decrease during the remaining part of the two seconds. The bottom part of Fig. 4 shows that in a little more than half a second the plasma line intensity drops to zero.

## 3. DISCUSSION

The observations described in the previous sections lead to two main conclusions.

The first conclusion concerns the nature of the overshoot. Figure 3 shows that a substantial overshoot in the 430 MHz enhanced plasma line can occur without any measurable attenuation of the 5.3 MHz HF wave in the ionosphere. In this and similar cases another explanation of the overshoot must therefore be found than that proposed by GRAHAM and FEJER (1976); one such explanation has been proposed by MULDREW (1988). No attempts will be made here to critically examine such alternative explanations of the overshoot. Similarly the experimental and theoretical work on the nature of the Langmuir turbulence that gives rise to the enhanced plasma line (DUBOIS *et al.*, 1988; SULZER *et al.*, 1989) is outside the scope of this paper.

The second conclusion is that for a heating frequency of 3.175 MHz a substantial part of the incident HF power goes into the excitation of parametric instabilities. Figure 4 shows that at the beginning of the cycling sequence of 2 s duration, near the end of the second 40 ms pulse, the observed 1.4 db attenuation means that about 28% of the incident power is dissipated by the Langmuir waves of ponderomotive type parametric instabilities. Near the end of the two seconds the observed 4.4 db attenuation means that about 64% of the incident power is dissipated by all parametric instabilities at that time, the observed 0.1 db difference between the attenuation at the end and the beginning of the last 40 ms pulse shows that of the 64% only less than 3% is accounted for by the ponderomotive type parametric instabilities.

It should be emphasized that the present results are based on relatively few observations. Further work is needed to establish whether there are no exceptions to the observed very small part of the incident power going into parametric instabilities for 5.3 MHz HF transmissions and the much larger part for 3.175 MHz HF transmissions at Arecibo.

One very interesting conclusion from the 3.175 MHz results is the relatively small part of the incident HF power going into ponderomotive type parametric instabilities and the very much larger part going into the thermal parametric instability associated with field aligned short-scale irregularities at the end of the 2 s cycling period.

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# FIRST OBSERVATIONS OF STIMULATED ELECTROMAGNETIC EMISSION AT ARECIBO

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*Abstract.* The first observations of HF heater stimulated electromagnetic emissions induced in the low-latitude ionospheric plasma above Arecibo, Puerto Rico, are reported. Many systematic spectral features of the emissions bear a close resemblance to those observed in ionospheric modification experiments in the auroral zone and scale in accordance with detailed theory. This proves that these sideband emissions are not dependent on specific geophysical conditions but are due to fundamental interaction processes in the ionospheric plasma. We also report the discovery of unique, short-lived HF sideband emissions that are less systematic than those observed previously and accompanied by a quenching of the HF enhanced plasma and ion lines in the Arecibo 430 MHz incoherent scatter radar spectra.

## Introduction

As was first shown in ionospheric modification (HF heating) experiments in 1981 in the auroral zone and later also at mid-latitudes, strong radio waves with frequencies that are lower than critical (typically 3-8 MHz) can excite secondary electromagnetic radiation in the ionospheric plasma [*Thidé et al.*, 1982, 1983; *Stubbe et al.*, 1984; *Boiko et al.*, 1985]. This radiation gives rise to systematic, richly structured sidebands, sometimes more than 100 kHz wide, asymmetrically around the ionospherically reflected heater wave. This phenomenon has become known as Stimulated Electromagnetic Emission (SEE).

At the time of discovery it was conjectured [*Thidé et al.*, 1982, 1983] that the SEE sidebands were induced by the strong HF heater wave within the ionospheric plasma. Through scattering and/or conversion mechanisms involving parametrically excited high-frequency electron waves and zero-frequency irregularities or low-frequency ion waves the observed frequency shifted electromagnetic radiation would result. A comprehensive and systematic study of the SEE phenomenon was undertaken by *Stubbe et al.* [1984] who found that even detailed structures of the spectra could be explained in terms of parametric decays and scattering/conversion mechanisms. Later, further analysis of the SEE spectra has widened our understanding of non-linear wave interactions in the ionosphere [*Leyser and Thidé*, 1988; *Leyser et al.*, 1989].

Here we report the first observations of SEE induced in a low-latitude overdense ionospheric plasma. The observations were made during HF heating experiments in March/April 1983 in Arecibo, Puerto Rico (geographical coordinates 18.35°N, 66.75°W, magnetic dip angle ≈ 49°). In order to minimize instrumental differences the same computer controlled sweep spectrum analyzer that was used in the earlier SEE experiments in Tromsø (69.58°N, 19.21°E, dip ≈ 77°) was utilized in the Arecibo experiments reported here. In addition, the HF sky wave was sampled and directly FFT analyzed on-line. The HF signals were picked up by a shortened, broad-band dipole feed near the focal point of the 305 m Arecibo antenna dish. In order to supplement the measurements at HF, the 430 MHz incoherent scatter radar was occasionally operated and the HF enhanced ion and plasma lines were recorded.

In general, the signal-to-noise ratio of the SEE was lower than is usually the case in Tromsø during geophysically quiet conditions. This is partly due to the fact that the effective radiated power in the Tromsø experiments is normally about 2–3 times higher than in Arecibo. Also, the level of background noise (natural as well as man-made) was rather high at the Arecibo Observatory, where all experiments were carried out. Furthermore, the measurements were often plagued by strong interferences from nearby HF transmitters requiring a reduction of the spectrum analyzer sensitivity in order not to jeopardize instrument linearity. All these things considered, the measurements in Arecibo were performed with a 10-15 dB higher effective noise floor than in Tromsø.

## Observations

An example of a comparatively strongly excited SEE spectrum, recorded with the spectrum analyzer on 6 April, 1983 at 20:59 local time (LT = AST = UT−4 h), is shown in Figure 1 where a broad, asymmetric spectral feature, downshifted from the transmitted strong 5.13 MHz signal by 7-15 kHz, can be clearly seen. This feature very much resembles the "downshifted maximum" (DM) which is one of the most common SEE features observed in the Tromsø experiments; see [*Thidé et al.*, 1982, 1983; *Stubbe et al.*, 1984]. Likewise, the weaker and more symmetrically shaped peak at about +5 kHz in Figure 1 is similar to the "upshifted maximum" (UM) feature also frequently seen in the Tromsø experiments. The spectrum displayed in Figure 1 is a typical example of all spectra observed during this period when the critical frequency was about 6 MHz, as indicated by an ionogram recorded at 20:57, and thus only slightly higher than the HF heater frequency itself. For comparison, a Tromsø SEE spectrum of similar type

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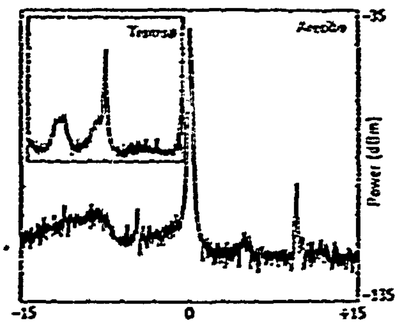


Fig. 1. Sky wave power vs. frequency offset $\Delta f$ from the HF heater frequency 5.13 MHz (60 MW ERP, *O* mode polarization) at Arecibo. The broad maximum at roughly −7 to −15 kHz is due to stimulated electromagnetic emission (SEE) induced in the ionosphere by the heater wave. So is also the weaker feature at about +5 kHz. The very narrow peaks at −5 and +10 kHz are interference from nearby HF radio transmitters. The inset shows a spectrum recorded at Tromsø for an HF heater frequency of 4.04 MHz. Otherwise the scales are identical to those in the Arecibo spectrum.

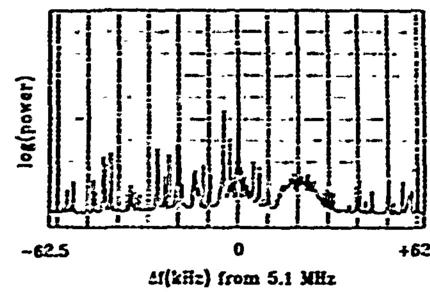


Fig. 3. FFT spectrum ±62.5 kHz around the HF sky wave at 5.10 MHz. The broad upshifted feature is due to SEE whereas the narrow peaks are interfering signals.

is inserted in Figure 1; see also Figure 2 in *Stubbe et al.*, [1984]. Comparing the spectra, one observes that the DM and UM features are excited in both Arecibo and Tromsø and that the similarities in the shape of the spectra are quite striking, particularly if one takes the reduced sensitivity into account. These similarities suggest that for the generation of emissions with this particular spectral distribution the same mechanisms are operative irrespective of latitude.

Induced sideband spectra of a different character were observed for a period of time on 4 April as exemplified by Figure 2. This Figure, which shows a spectrum with a strong feature, peaking at almost exactly −2 kHz from the transmitted 5.1 MHz wave, was recorded at 17:50 LT. Figure 2 also shows that during this period virtually all SEE was concentrated in a much narrower range of sideband frequencies. In contrast to the conditions at the time of

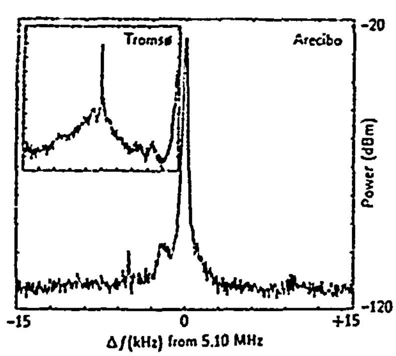


Fig. 2. Same as Fig. 1 except for the Arecibo HF frequency (5.10 MHz) and that now the broad downshifted feature is almost totally absent while there is a strong, narrow SEE peak at −2 kHz. Interfering signals are present at −5 kHz. The inserted Tromsø spectrum, containing a SEE peak also at about −2 kHz show additional SEE features absent in the Arecibo spectrum. Presumably, this is in part due to the higher effective noise floor in Arecibo.

recording the spectrum in Figure 1, the spectrum in Figure 2 was recorded when the critical frequency was much higher (10 MHz) than that of the HF wave, as determined from an ionogram taken at 18:02 LT. Again, accounting for the higher noise floor in the Arecibo spectrum, we see that we can relate this spectrum to similar spectra observed at Tromsø under comparable conditions, as illustrated by the inset in Figure 2 and by those in Figure 4 in *Stubbe et al.*, [1984]. Hence, we identify the −2 kHz peak with the "downshifted peak" (DP) feature observed earlier only at Tromsø; see also Figure 1 of *Leyser and Thidé* [1988].

Yet another type of SEE feature was identified in the real-time FFT spectra of 31 March. During the short period 21:31–21:33 LT an emission with a broad spectral feature was excited in the upper sideband, with its maximum at roughly +20 kHz. One example is shown in Figure 3. This feature could be similar to the "broad upshifted maximum" (BUM) feature often observed in the Tromsø experiments [*Stubbe et al.*, 1984] but may also be quite different. We need more observations to be able to make a detailed comparison of the two.

Based on the above observations and the fact that the shapes of the spectra are very reproducible and stable for long periods of time, we conclude that the types of stimulated emissions discussed are manifestations of low-latitude counterparts of basic ionospheric wave-wave interaction phenomena occurring during ionospheric modification at higher latitudes and that special ionospheric conditions are, in general, not necessary for their excitation.

On 7 April, however, new and much more unsystematic SEE features were discovered and we therefore describe in some detail the observations made on this day.

Data from the period 17:28–19:28 LT on 7 April are summarized in graphical form in Figure 4. The top panel (a) shows the HF effective radiated power (ERP) versus time; intervals with 1 kHz modulation of the HF are indicated by bold lines. Using a high-resolution multi-pulse technique on the 430 MHz incoherent scatter radar [*Sulzer et al.*, 1984], the time variations of the power in the HF enhanced downshifted ion and upshifted plasma lines as well as the height of maximum HF enhancement of the plasma line were measured. The results are displayed in panels (b), (c), and (d) of Figure 4, respectively. We see that the enhancement was comparatively low during the periods of HF modulation and reduced HF ERP. It should be noted that while the HF ERP was held constant at 24 MW until 18:45 LT, the power in the plasma line decreased steadily until 18:38 LT.

At the same time there appeared strong but unusually erratic spectral features in the HF sidebands out to at least

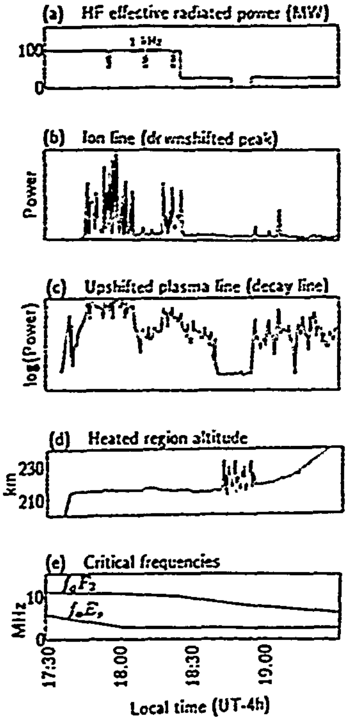


Fig. 4. Parameters/measured values *vs.* local time (horizontal axis; 6 min between tic marks) on 7 April, 1983: (a) Effective radiated HF power. Note the periods of 1 kHz modulation (bold lines) and the absence of HF at 18:45–18:53 LT. (b) Power (linear scale) in the downshifted HF enhanced ion line of the 430 MHz incoherent scatter radar. (c) Power (logarithmic scale) in the upshifted HF enhanced plasma line (decay line). (d) Altitude of the region of maximum plasma line HF enhancement. (e) Critical frequencies as determined by ionograms taken at certain discrete times.

±100 kHz from the heater frequency as shown in Figure 5; the central peaks show that the reflected HF sky wave was fairly constant in amplitude throughout the whole period. These strong and wide SEE spectra are unique and have not been reported from any other SEE experiment to date. By comparing with Figure 4 we see that these unusual sidebands occurred just at the time when the HF enhancement in the 430 MHz radar spectra were no longer above the detectability level. One immediate conclusion is that during this period the threshold for the parametric decay instability (PDI), in which the HF wave decays into electrostatic waves with the correct wave vector to be observable by the 430 MHz radar, is no longer exceeded but other processes yield the observed electromagnetic radiation near the HF frequency.

Ionograms taken at irregular intervals show that when the above measurements on 7 April started a blanketing sporadic $E$ layer, with a maximum plasma frequency $f_oE_s$ of about 4.8 MHz, i.e., slightly below the HF frequency of 5.13 MHz, was present. At the same time the $F$ layer maximum plasma frequency $f_oF_2$ was about 11.5 MHz. As the experiment proceeded the $f_oE_s$ and $f_oF_2$ dropped steadily. This is depicted in Figure 4 panel (e). Note the consistency between the change in $f_oF_2$ and the change in interaction region altitude in panel (d). No interaction in the $E$ layer was detected by the 430 MHz radar.

## Discussion

The broad asymmetric DM feature in the lower sideband of the spectrum displayed in Figure 1 was explained by *Stubbe et al.* [1984] in terms of scattering of parametrically excited Langmuir waves off low- or zero-frequency ion irregularities. Using the fact that emissions generated far below the reflection height have larger offsets and a favorable spatial weighting compared to the emissions generated with small offsets very near the reflection height it was possible to predict an enhanced SEE intensity at about $2 \times 10^{-3} f_0$ in good agreement with observations; see Subsection 4.2 in *Stubbe et al.* [1984]. However, the shape of the DM feature, often with a sharp cut-off edge on its high side as shown in Figure 1, could not be explained by this theory. Later detailed analysis of the interaction processes have shown that both the position and shape of the DM feature can be very well explained in terms of interaction between upper-hybrid waves, excited linearly through scattering of the pump off induced striations at the upper hybrid layer, decaying parametrically into escaping $O$ mode EM radiation and lower-hybrid waves propagating in a very small, but finite angular range around perpendicularity to the geomagnetic field [*Leyser et al.*, 1989; see also *Murtaza and Shukla*, 1984]. Unlike the maximum of the DM feature, the position of its high-frequency cut-off edge should correspond to the local lower hybrid frequency and be more or less independent of pump frequency. Comparing the two spectra in Figure 1 one sees that the lower-hybrid frequency at Tromsø would be about 8 kHz and about 7 kHz at Arecibo in good agreement with the actual geophysical conditions at the two sites. We therefore consider the DM results presented here to support the more accurate theory of *Leyser et al.* [1989]. The fact that striations are needed to explain the DM could be a reason why the DM emissions are more difficult to observe at Arecibo than at Tromsø where striations are more easily generated.

The DP was in *Stubbe et al.* [1984] attributed to the first maximum of the standing HF radio wave, assumed, for simplicity, to be an Airy pattern. However, in *Stubbe et al.* [1984] the terrestrial magnetic field was not properly taken into account. Correcting for this, one finds that the essen-

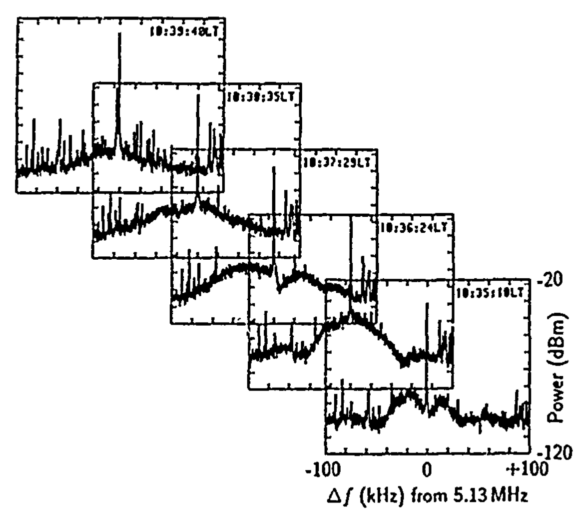


Fig. 5. Five consecutive HF spectra recorded between approximately 18:35 LT and 18:40 LT on 7 April; cf. Fig. 4.

tial difference is that the effective scale height for a purely linear electron density profile with true scale height $H$ is, at least for the first few standing wave maxima, roughly $H \sin^2 \vartheta$, where $\theta$ is the angle between the terrestrial magnetic field and the vertical. This deficiency was discussed by *Leyser and Thidé* [1988] who calculated the position of the DP feature, taking both the magnetic field and the plasma depletion due to the pump ponderomotive force into account. It turned out that with these two corrections *Leyser and Thidé* [1988] were able to make predictions of the position of the DP which agree very well with the experimental results both from Tromsø and Arecibo, as presented in Figure 2. Again, our measurements at a different geomagnetic latitude lend support to the more detailed theory.

As has been noted in the Tromsø experiments, the broad upshifted maximum (BUM) feature in the SEE spectrum usually appears only for pumping at frequencies very near harmonics of the electron cyclotron frequency [*Leyser et al.*, 1989]. If the upper sideband feature seen in Figure 3 is an Arecibo counterpart then the 5.1 MHz pump frequency would indicate the 5th harmonic of an electron cyclotron frequency of 1.02 MHz which is roughly equal to the value predicted by magnetic field models for the ionospheric $F$ region under normal conditions.

The BUM feature in Tromsø seems to be correlated with the occurrence of intense striations which grow on a slow time scale. However, in the Arecibo experiments reported here we had no way of measuring the striation intensity or the growth time of the observed upshifted feature, so it is possible that the SEE emission in Figure 3 has its origin in quite a different mechanism. Upshifted features which do not fit into the "normal" parametric decay cascade scheme, have been observed in incoherent scatter spectra at Arecibo [*Djuth et al.*, 1986] and in numerical simulations by *DuBois et al.* [1988], where they are attributed to "free" Langmuir modes resulting from collapsing cavtions.

The strong erratic HF emissions shown in the spectra in Figure 5 have only been observed once at Arecibo and never at Tromsø. They are therefore very difficult to analyze and explain in terms of plasma processes. One possible explanation might be that during the few minutes this phenomenon was observed, the ionosphere was perturbed by a naturally occurring traveling disturbance of a size comparable to the HF wave length, producing strong local plasma gradients in varying directions off the vertical. Whereas this might lead to enhanced pump intensity, due to focusing, and a strong local excitation of secondary EM radiation, the parametrically excited Langmuir waves would not be able to propagate to a point in space where they could scatter the vertically propagating 70 cm probing waves of the 430 Mhz radar. Clearly, this phenomenon has to be studied in greater detail with a good support of other diagnostics.

In conclusion, we have shown that the SEE phenomenon is a global one, not requiring special (e.g., auroral) conditions and that certain prominent features in the SEE spectra depend on the local geophysical parameters in a way predicted by detailed theory. We have also found new SEE features which need further study.

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